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NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

PIRATE MOTHER SHIP WARNING AND REPORTING SYSTEM

(PMSW&RS)

by

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The Pirate Mother Ship Warning and Reporting System (PMSW&RS) analysis identifies a suitable and effective combination of unmanned aerial systems land launched from regional main operating bases (MOB) or commercial airfields to provide persistent intelligence, surveillance, reconnaissance, and tracking of Pirate Mother Ships that are prowling the shipping lanes for commercial vessels transiting across the Horn of Africa (HOA). The team developed a systems concept, the context, and a requirements hierarchy to support mission objectives. Architectural baselines were developed to identify key design characteristics and to provide insight into the value system design, analysis, modeling, and research efforts. System modeling using IBM Rational Rhapsody toolset, OMOE analysis, and CAIV analysis confirm that the highest value solution uses the LEMV.

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ABSTRACT

The Pirate Mother Ship Warning and Reporting System (PMSW&RS) analysis identifies a suitable and effective combination of unmanned aerial systems land launched from regional main operating bases (MOB) or commercial airfields to provide persistent intelligence, surveillance, reconnaissance, and tracking of Pirate Mother Ships that are prowling the shipping lanes for commercial vessels transiting across the Horn of Africa (HOA). The team developed a systems concept, the context, and a requirements hierarchy to support mission objectives. Architectural baselines were developed to identify key design characteristics and to provide insight into the value system design, analysis, modeling, and research efforts. System modeling using IBM Rational Rhapsody toolset, OMOE analysis, and CAIV analysis confirm that the highest value solution uses the LEMV.

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EXECUTIVE SUMMARY

The Program Executive Office for Unmanned Aviation and Strike Weapons requested the Naval Postgraduate School conduct an investigation into the rapid application of unmanned aerial systems (UASs) be completed to counter the extension of piracy operations into blue water off the Horn of Africa (HOA). The request was focused on closing the capability gap pending the fielding of systems currently in development, namely the Broad Area Maritime Surveillance (BAMS) Unmanned Arial System (UAS). The Pirate Mother Ship Warning and Reporting System (PMSW&RS) project team focused on understanding the current operational environment and the tactics necessary for detecting, locating, classifying, identifying, tracking, and reporting on pirate activities in order to counter piracy off the Horn of Africa. In addition, the inventory of currently available unmanned aerial systems, as well as systems available by the end of calendar year 2012, was reviewed for applicability to the problem at hand. Four research questions were posed and endorsed by stakeholders:

- What capability gaps need to be addressed with respect to countering the pirate application of mother ships?
- Can formation and application of a system comprised of existing or near term intelligence, surveillance, and reconnaissance (ISR) assets meet stakeholders' needs for countering the pirate application of mother ships?
- What characteristics, signatures and patterns mark a pirate mother ship?
- What sensor payload requirements are needed to exploit the characteristics, signatures and patterns of pirate mother ships?

During the needs analysis phase, an iterative process between the team and stakeholders resulted in eight top-level measures of effectiveness (MOEs), Table 1.

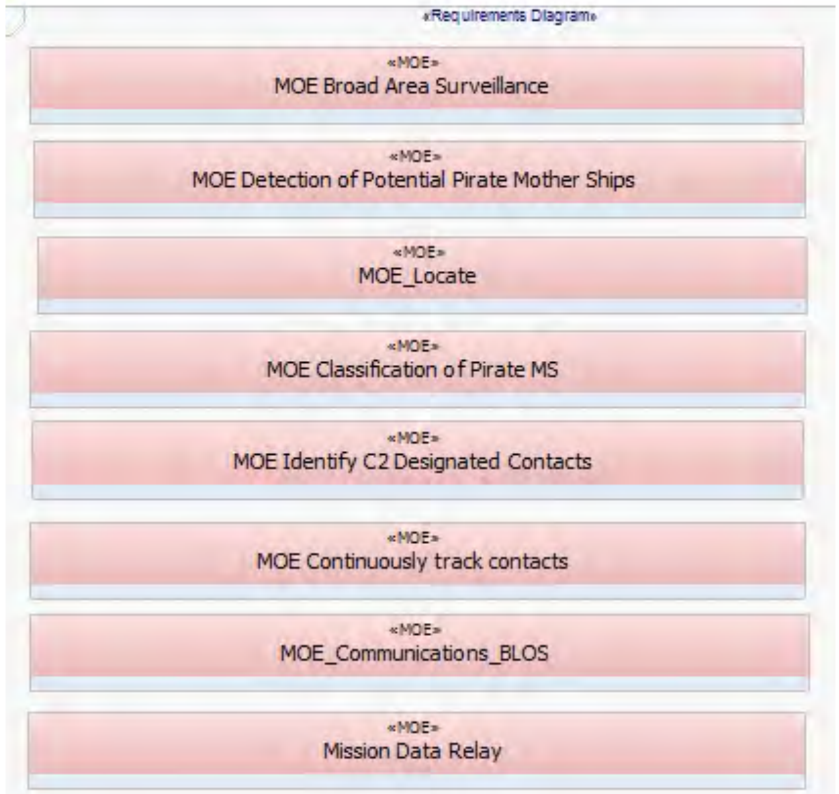

Table 1. “Measures of Effectiveness.” This table shows the measures of effectiveness most relevant for interdicting pirates or identifying pirate mother ships.

A broad market survey was conducted that examined various mission concepts and systems. The use of manned vehicles for detecting, locating, classifying, identifying and tracking was discounted early in the analysis due to the effective time on station durations required to complete the mission. The Long Endurance Multi-intelligence Vehicle (LEMV), Heron TP, and Guardian were selected as viable UAS options based on their endurance, mission payloads, availability and cost effectiveness.

Some research was performed to determine the viability of using weaponized UASs and directly supporting interdiction, but in interviews with past and current UAS operators, it was suggested that legal challenges superseded technical challenges. As a result, the focus was shifted strictly towards ISR. Based on these decisions, assumptions and constraints were generated to clearly bound the scope of the analysis that would be performed.

Measures of Performance (MOPs) were derived from MOEs. Using the MOEs and MOPs, functional, physical, and operational architectures were designed. Baseline development and analysis was also performed. Research into current UAS sensor capability, UAS effective time on station (ETOS), and speed formed the basis for detailed assessment of PMSW&RS capabilities and limitations. A Quality Function Deployment (QFD) analysis used the MOEs through the functional and physical architecture baselines in order to weight the PMSW&RS design characteristics. The resulting Value System Design formed a level base for Overall Measure of Effectiveness (OMOE) analysis of the PMSW&RS physical alternatives: LEMV, Heron TP, and Guardian.

	# UAV to Complete Mission (Threshold)	# UAV to Complete Mission (Objective)	Mission Duration (Hrs)	Total Cost (Threshold)	Total Cost (Objective)	Scaled Cost (Threshold) FY12 $M	Scaled Cost (Objective) FY12 $M	Decision Matrix Total Score
Heron	2	2	168	$ 2,251,200	$ 2,251,200	2.251	2.251	0.780
LEMV	4	5	168	$ 1,411,200	$ 1,764,000	1.411	1.764	0.789
Guardian	4	4	168	$ 3,158,400	$ 3,158,400	3.158	3.158	0.690

Table 2. “OMOE Score versus Initial Procurement Costs.”

Comparison of CAIV scores noted in Table 2 shows that LEMV would provide the best solution by meeting both the threshold and objective performances at the lowest cost. Microsoft Excel modeling was used for the OMOE and cost as an independent variable (CAIV) analyses by providing the number of assets needed from each UAS to meet the following thresholds and objectives.

- Detection range: Range to detect RCS 25 square meters (m^2) at minimum of 20k ft altitude, Threshold: 80 miles, Objective: 200 nautical miles
- Track Capacity: number of surface tracks maintained while in sensor view, Threshold: 150, Objective: 200
- Endurance: Hours on station at mission radius, Threshold: 12, Objective: 24.

- Detection Accuracy: Surface vessel detection range of accuracy for RCS (m^2) at 20k ft, Threshold: 500 ft, Objective: 200 ft
- Speed: UAS mission loiter speed, Threshold: 80 knots, Objective: 200 knots
- LOS: Line of Sight communications capability. Data was not available on all candidate UASs, except if LOS capability was on board, Threshold: 40 nautical miles (nmi), Objective: 182.4 nautical miles (nmi)
- BLOS: Beyond Line Of Sight communications, range of radio with use of SATCOM, Data was not available on all candidate UASs, except if LOS capability was on board, Threshold: 40 nautical miles (nmi). Objective: 192 nautical miles (nmi)
- NIIRS: National Imagery Interpretability Rating Scales number for quality of imagery, Threshold: 7, Objective: 8
- Speed: Threshold: 80 knots Objective: 200 knots

OMOE analysis and Microsoft Excel modeling both indicated the mission could be completed by each platform, given the right number of assets. The optimum platform for mission success at both threshold and objective probabilities of detection is the LEMV.

LEMV dominated in cost at the threshold and objective level, 1.4M and 1.7M respectively, as well as performance at a OMOE value of .789. Heron TP achieved the next lowest cost at both the threshold and objective values of 2.25M along with the second best OMOE score of .780. Of the three potential solutions considered, Guardian had the most expensive cost at the threshold and objective levels with a value of 3.1M along with the worst performance OMOE value of .690. Notably, the Guardian's speed outperformed LEMV, enabling a higher search rate. Heron TP's loiter altitude of 40,000 feet enabled a wider field of view and expanded detection range. The LEMV boasts 21-days of effective time on station (ETOS). This and its low cost in comparison to other UASs were the key attributes in selection.

The PMSW&RS team recommends the LEMV as the recommended solution to satisfy stakeholder needs because LEMV achieves an acceptable OMOE score at the lowest operating cost.

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I. BACKGROUND

A. PIRACY OFF THE HORN OF AFRICA

The ability to defend commercial ships against pirate attacks has proven especially difficult for the international community. The recent international response to piracy in the Gulf of Aden has been successful in reducing the success of pirate attacks but has resulted in new tactic by pirates. These new tactics involve the use of mother ships to extend operations off the coast of Africa beyond the typical range of standard skiffs. Not only do these ships extend range, but they function as “floating bases loaded with skiffs” and Fifth Fleet Vice Admiral Mark Fox has called them “game changers.” Multiple military organizations are involved in the counter-piracy operations off the Horn of Arica. Chief among these organizations are: NATO, EUNAVFOR, Combined Task Force (CTF) 151, CTF 150, and ALINDIEN operated by the French Force Commander, Indian Ocean (Fellman 2011).

As a global force, the United States Navy is relied upon to protect American commercial shipping anywhere around the world. At present, the greatest threat to commercial shipping is in the area of the Horn of Africa, as depicted in Figure 1, “Horn of Africa Area of Responsibility (HOA AOR).” Current piracy tactics allow for operations throughout this area by using motherships, usually converted from fishing trawlers, dhows or small transport ships by the pirates after being captured (Naval Criminal Investigative Services, Multiple Threat Alert Center 2011).

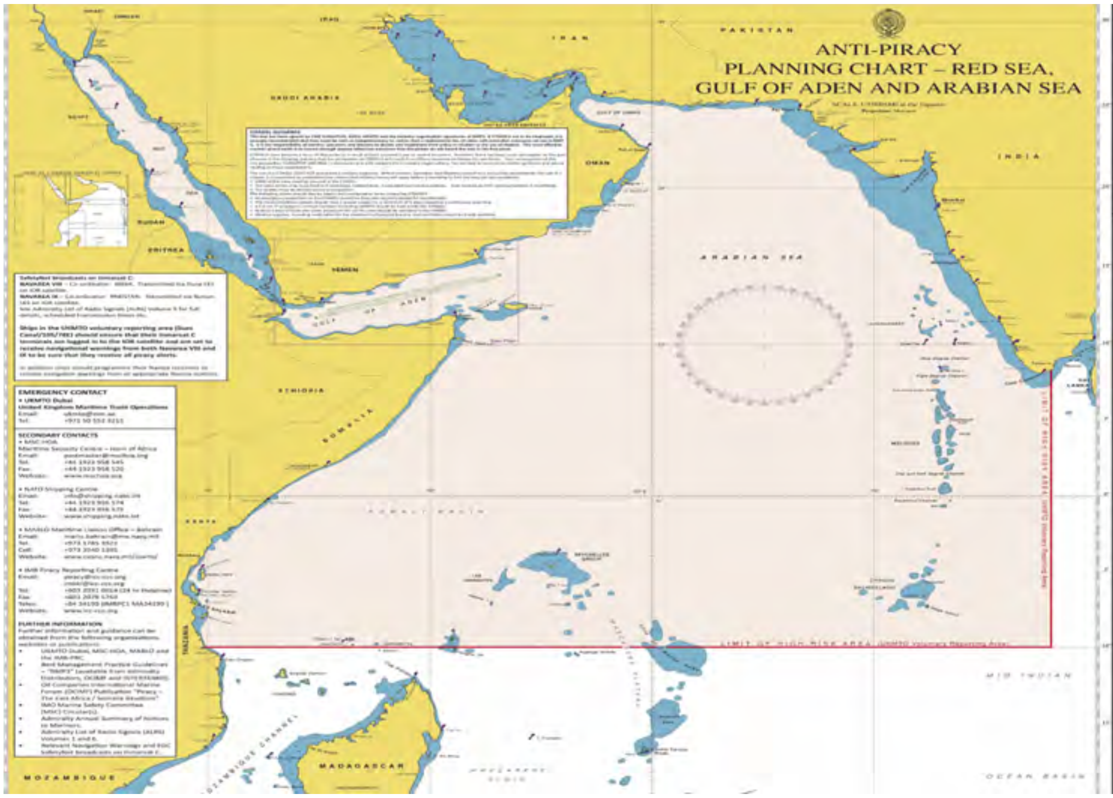

Figure 1. “Horn of Africa Area of Responsibility (HOA AOR).”(The United Kingdom Hydrographic Office 2010)

B. WEATHER

The size of the area and the quantity of commercial traffic make escorting ships via surface security ships cost prohibitive. The 1958 Geneva Convention and the 1982 Safety of Life At Sea (SOLAS) Convention both direct nations to cooperate in suppression of piracy on the high seas (Department of the Navy & Department of Homeland Security, 2007). Countering the piracy threat requires a multifaceted approach with all stakeholders contributing and the world’s navies providing cost-effective solutions. One such solution area is the gathering of intelligence, a capability that is almost solely possessed by nation states and their acting governments. Naval forces need better intelligence to counter piracy and commercial fleets need access to intelligence to develop and apply tactics in order to avoid contact with pirates.

Pirate attacks have remained unabated and are getting bigger and bolder according to the IMB report dated Thursday July 14, 2011 (International Maritime Bureau 2011). According the IMB, “Pirate attacks on the world’s seas totaled 266 in the first six months of 2011, up from 196 incidents in the same period last year” (International Maritime Bureau 2011). Further, from February to July of 2011 “Somali pirates attacked more vessels than ever before” (International Maritime Bureau 2011) and in “June, for the first time, pirates fired on ships in rough seas in the Indian Ocean during the monsoon season” (International Maritime Bureau 2011). Previously this has been a rare occurrence due to the difficulty of boarding a moving ship in rough seas (International Maritime Bureau 2011).

As the piracy escalates and becomes widespread in the Indian Ocean, there is a corresponding increase in cost of transporting goods not only between European and Asian countries but around the world. According to Major Dennis Sampson, “pirates retain an advantage by operating within or escaping to locations within the territorial waters of countries unable to oversee or lawfully take action against pirates” (Sampson 2009).

The primary objective of piracy is to exact a ransom for the release of the crew members, the ships, and their cargo. It is becoming a booming enterprise for the Somali pirates whose income from ransom has been estimated to be about 39 million Euro (about $58 million) in 2009 (Utler 2011) and $238 million in 2010 (Gill 2011). However, indirect costs of piracy are much higher and estimated to be between $7 to 12 billion as they also include insurance, naval support, legal proceedings, re-routing of slower ships, and individual protective steps taken by ship-owners (Gill 2011).

Given the attractive financial gains from piracy, a 2011 report published by Geopolicity Inc. indicates that the number of pirates could double by 2016, with an increase of 400 pirates each year. This incentive to commit piracy would earn a pirate up to $79,000 per year equating to almost 150 times their country’s national average wage (Owen 2011).

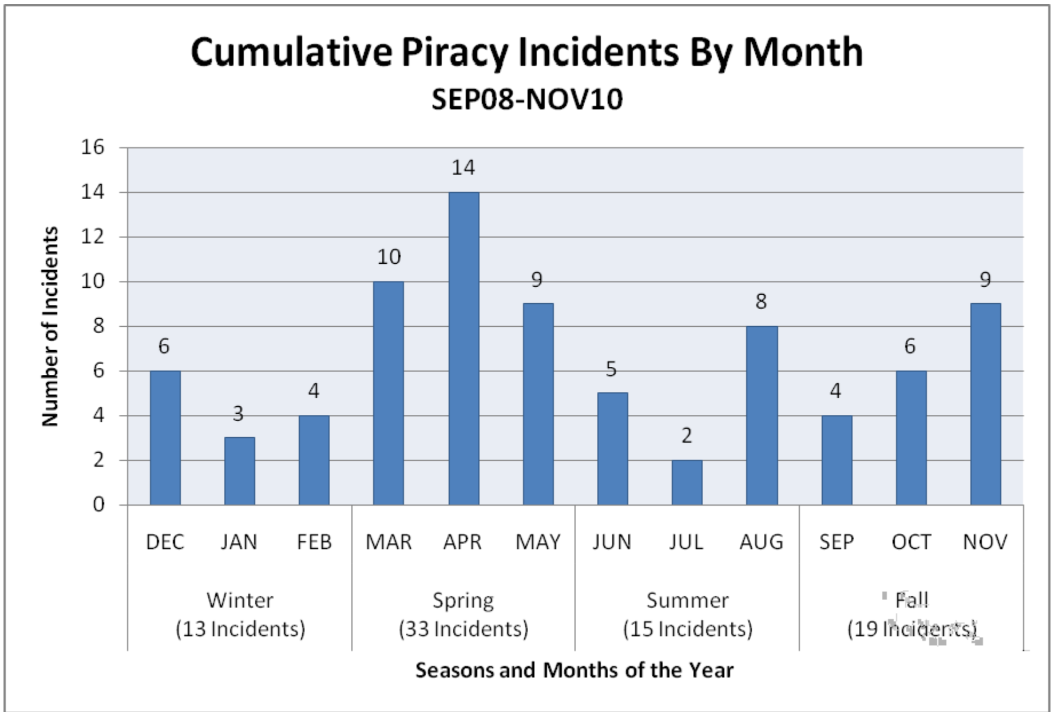

Figure 2. “NCIS Pirate Seasonal Attacks.” (Unclassified Data)

The weather within the HOA AOR can be troublesome for pirate operations, especially during the monsoon seasons. There are two monsoon seasons, one in the summer between June and August, and the other in the winter between December and February. Piracy attacks during the summer monsoon season are half the normal monthly rate (Naval Criminal Investigative Service 2011). Figure 2, “NCIS Pirate Seasonal Attacks,” relates pirate attacks to the seasons of the year. The summer monsoon produces waves up to seven and eight meters high and winds above thirty five knots while the winter monsoon causes waves up to two meters high and gusts of up to eighteen knots.

“In the last six months, Somali pirates attacked more vessels than ever before and they’re taking higher risks,” said International Maritime Bureau Director Pottengal Mukundan. “This June, for the first time, pirates fired on ships in rough seas in the Indian Ocean during the monsoon season. In the past, they would have stayed away in such difficult conditions.” He warns that “masters should remain vigilant.” (International Maritime Bureau 2011)

C. TRENDS AND CHARACTERISTICS

1. Trends of Piracy Tactics

a. Conditions in Somalia: Early History

Piracy off the coast of Somalia is a result of regional instability and the lack of rule of law in Somalia (U. N. Council 2010). In January 1991, President Siad Berre was forced out of the capital and the government collapsed. The fall of the government led to widespread poverty and the split of the nation into autonomous clan-led regions. The result of the collapse of the central controlling authority of the nation began a slide into poverty for the people, lack of employment, and damage to the fishing trade by illegal fishing and hazardous dumping (Expert Group on Piracy off the Somali Coast 2008). As the piracy increased, the fishing trade became more dangerous. Pollution from illegal dumping and over-fishing by foreigners has resulted in decreased yields for Somali fisherman. This forced an increase in piracy because piracy was seen by many fishermen as the only option for survival. The choice available to people who previously relied on fishing for their livelihood was between living in destitution, afraid of the powerful or joining one of the organized bands of buccaneers.

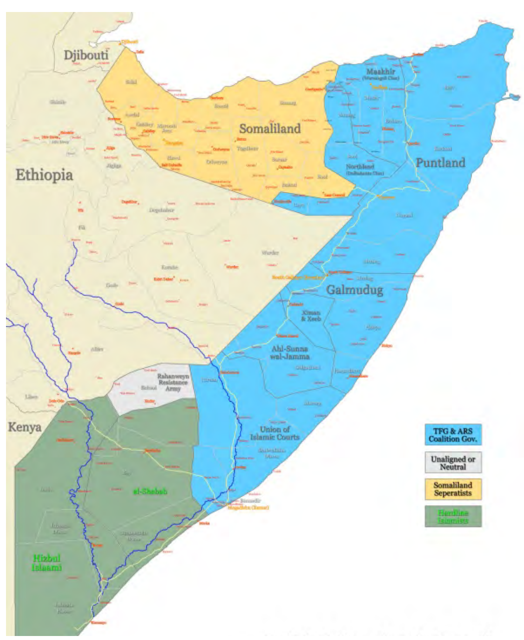

Figure 3. “Piracy Ports.” (Dahl 2011).

By the middle of the previous decade, there were five main piracy ports in Somalia; Eyl, Hobyo, Hardheere and Caluula (Carafano and Rodeback 2011). These ports are well organized, well-armed and protected from local authorities. Currently, piracy in Somalia is centered in the Puntland region. It is suspected that piracy has penetrated the local government where officials are suspected of direct involvement in piracy activities (Expert Group on Piracy off the Somali Coast 2008).

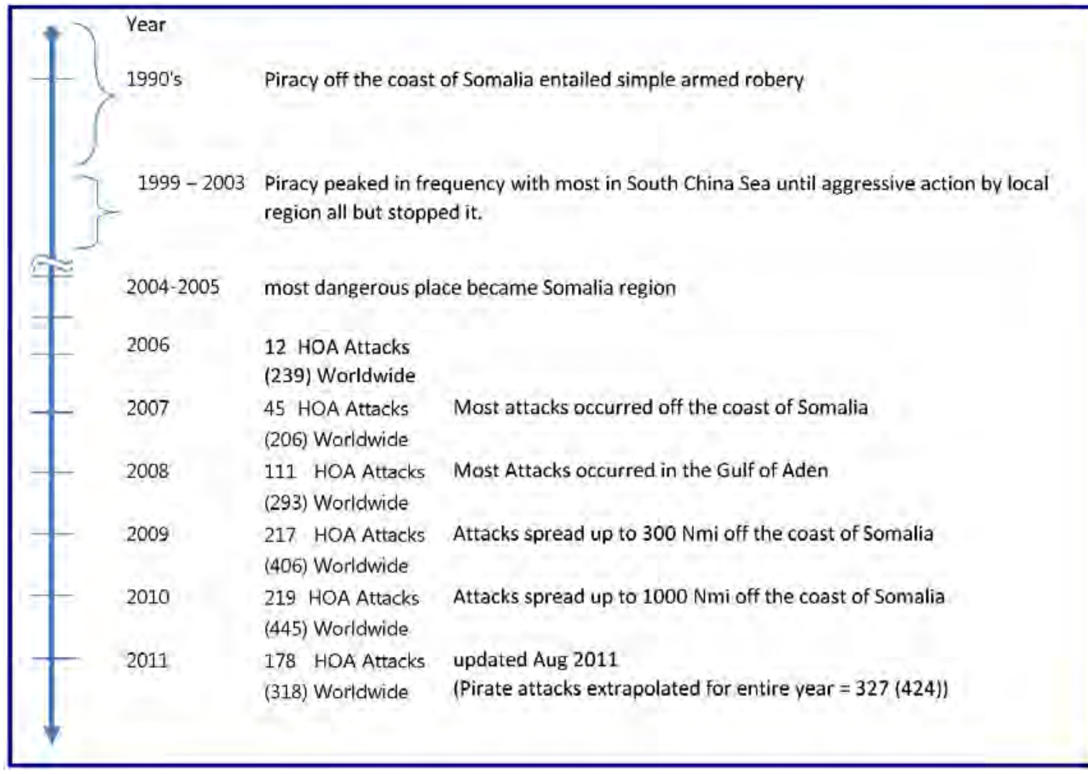

Figure 4. "Timeline of Piracy in HOA AOR." (Carafano and Rodeback 2011.)

b. Evalutation of Somali Pirate Tactics

In the 1990s, piracy off the shore of Somalia was limited to small groups of young men engaging in armed robbery of fishing boats and other small craft. They employed small skiffs with outboard motors and patrolled the littoral areas. Local fishermen would supply their fishing skiffs in exchange for payments that far exceeded what they could make fishing. As the turn of the century approached, these groups became better tied together and developed into a clan-controlled group that was better organized and effective. By 2005, the HOA region became one of the most dangerous pirate hotspots in the world. This was due in part to the increasing local organization of pirates as well as the local crackdown in the South China Sea where piracy was greatly reduced.

Figure 5. “Pirate Skiff.”

In the early 2000s, the pirates off the coast of Somalia began to hijack larger ships, as well as fishing vessels and private yachts. The hijacked ships are taken to various pirate ports on the coast of Somalia, depending on the origin of the pirate clan. Ransoms for the crew, ship and cargo would be negotiated with the help of the clan elders. Their tactic was to launch from beaches in twenty foot long pirate skiffs, idle off shore up to fifty nm, and wait for a target to cross their path (Expert Group on Piracy off the Somali Coast 2008). These skiffs could move as fast as thirty knots powered by eighty-five horsepower outboard motors. They targeted slow moving vessels and those with a low freeboard.

By 2008, there were significant attacks resulting in a change in commercial shipping tactics. Commercial ships avoided the region of Somalia and moved further out to sea as seen in Figure 6, “Activity Trend 2007-2010.” The Somali pirates responded by adjusting their area of patrol. The pirates moved their attacks to the Gulf of Aden where there is high commercial shipping traffic, as many as 33,000 vessels per year (Ploch, et al. 2011).

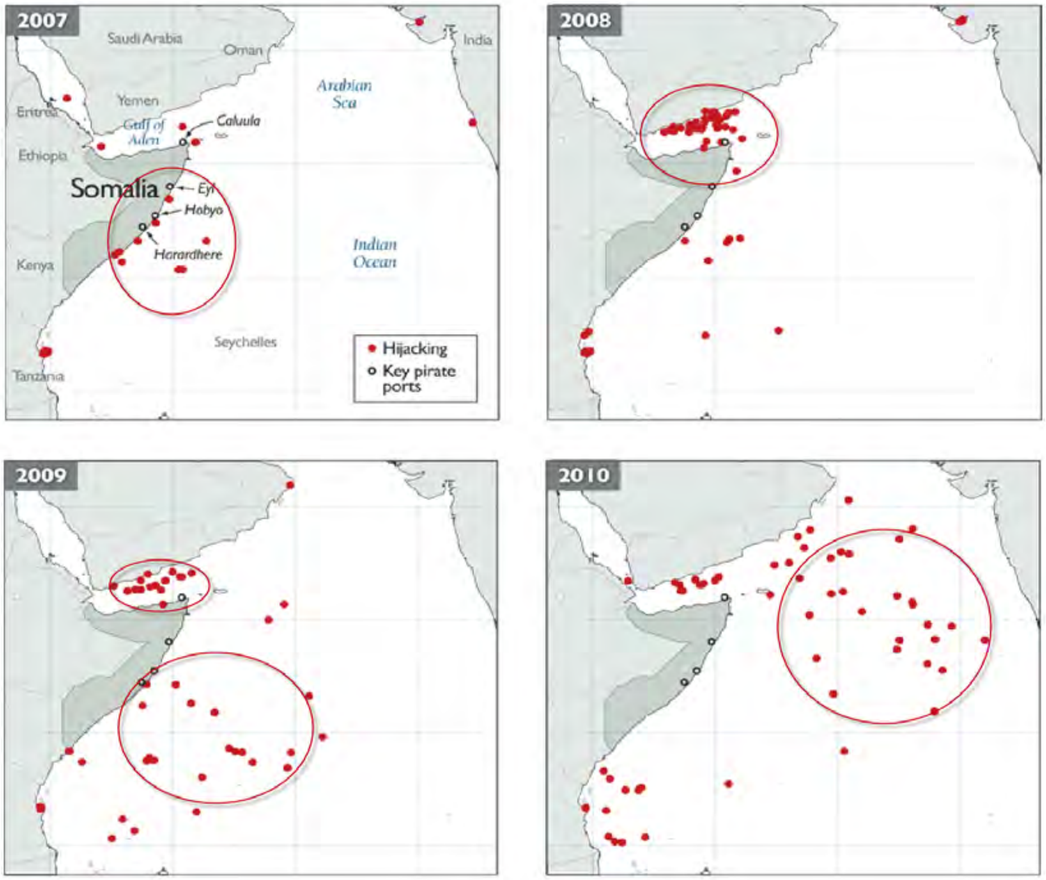

Figure 6. "Activity Trend 2007-2010." (Carafano and Rodeback 2011). In 2008, pirates moved operations from the coast of Somalia to the Gulf of Aden. By 2010, the pirates moved from the Gulf of Aden further off the coast of Somalia.

Their tactics remained much the same as the previous year. The pirates would wait for a target and then chase them in a small craft equipped with an outboard motor. If a ship is successfully captured, the pirates take the vessel to one of the pirate ports and demand ransom for the crew, ship, and cargo.

As the international community increased the protection of commercial shipping in the Gulf of Aden in 2009, the Somali pirates again moved out to sea. Some of the captured ships would be used as mother ships to tow the skiffs up to 300nm off shore. The motherships would move into the shipping lanes and search for targets. Once one was found, the skiffs would be launched and several would swarm the target. Upon reaching the target, seven to ten pirates would board the ship using ladders and grappling hooks.

In response to this change in tactics, the international community published a best practices report (The UK Maritime Trade 2011) to deter piracy in the Gulf of Aden and off the coast of Somalia. The commercial ships also employed passive methods to escape during attacks. One of the best methods was to keep a watch, and when a potential threat was spotted, increase speed and veer away.   Pirates adapted their tactics by employing larger 150 horsepower engines on their skiffs (Expert Group on Piracy off the Somali Coast 2008).

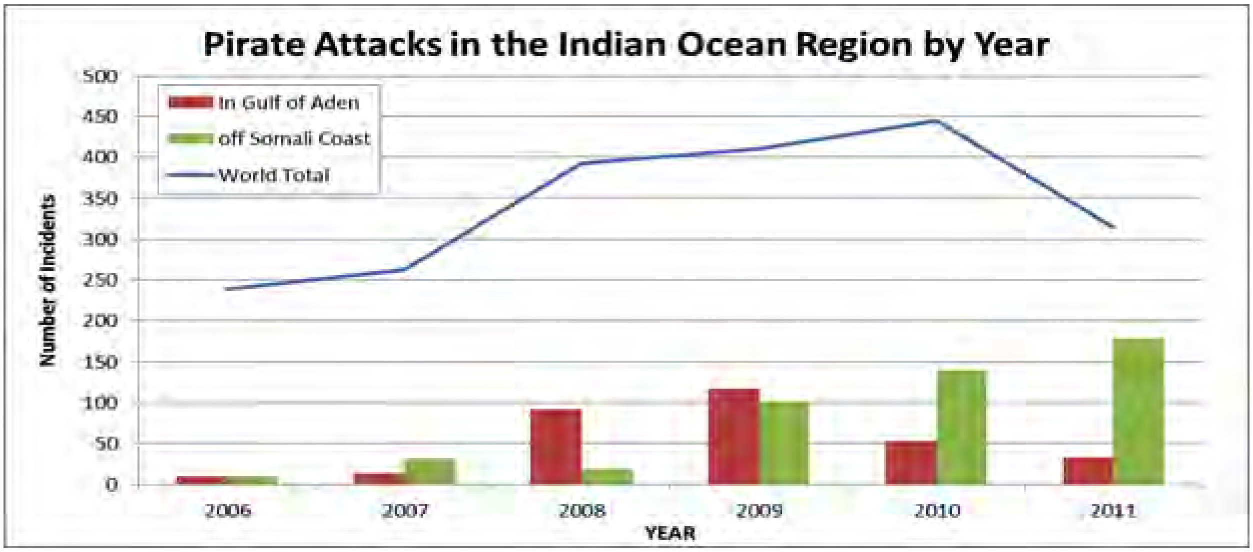

Figure 7. "Pirate attacks in the HOA AOR moved from the Gulf of Aden to off the Somalia coast." Data compiled from the following sources: (U. N. Council 2010) (U. S. Council, Pursuant to Security Council Resolution 1846 2008) (U. S. Council, Somalia pursuant to Security Council Resolution 1872 2009) (ICC-International Maritime Bureau 2010) (Major Dennis w. Sampson 2009) (Ploch, et al. 2011) (UNODC 2010)

In 2010, the pirate activity moved further out into the Indian Ocean, as far as 1000 nm. Pirate attacks are more widespread and cover a larger area when compared to previous years, as seen in Figure 7. This was achievable by converting large merchant vessels into "mother ships." With the increase in passive deterrents to boarding and the high speed run to escape pursuit, the pirates have used small arms fire and rocket propelled grenades in an attempt to intimidate the masters of vessels into stopping and once boarded, to enter the onboard citadel (Operations August 2011).   To facilitate locating vessels out at sea, the pirates became more sophisticated by employing global positioning system equipment and began monitoring ship Automatic Identification System (AIS) signals to find prey (Expert Group on Piracy off the Somali Coast 2008).

Currently, the pirates are increasing attacks up to 1000 nm into the Arabian Sea and the Indian Ocean. Starting in 2009, the international community began an anti-piracy operation called Task Force 151. This task force is sanctioned to patrol the Gulf of Aden and the east coast of Somalia to render aid to ships in distress from attacks.

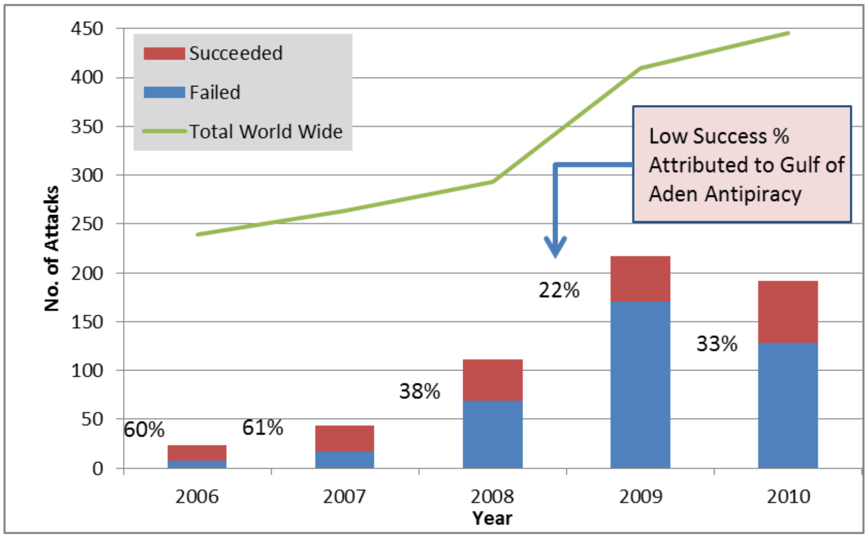

Figure 8. "Pirate Attacks per Year." Successes per attempted piracy events in the HOA AOR by year (Ploch, et al. 2011) (Carafano and Rodeback 2011) (UNODC 2010)

PIRACY ACTIVITY IN AREA OF INTEREST BY YEAR					
	2006	2007	2008	2009	2010
Gulf of Aden	10	13	92	117	53
Somalia	10	31	19	80	139
Somalia/GoA Attacks	20	44	111	217	192
Somalia/GoA Hijackings	12	27	42	47	64
PERCENT SUCCESS	60%	61%	38%	22%	33%
TOTAL WORLD WIDE	239	264	293	410	445

Table 3. "Piracy Activity in Area of Interest by Year." Piracy events in the HOA AOR (Ploch, et al. 2011) (Carafano and Rodeback 2011) (UNODC 2010). Percent success by pirates has been reduced through intervention even with an increase in frequency of attacks, but more can be done.

The creation of taskforce 151 has resulted in the incarceration of over 600 suspected and convicted pirates (U. N. Council 2010). Prior to 2009, there was a general "catch and release" approach to piracy. In response to the international practice, pirates have used more aggressive tactics and even murdered hostages. Al Shabaab, a group some believe to be a terrorist movement, has been reported to have regional ties to the pirate groups in Somalia. Allegedly, some pirate groups approached Al Shabaab for combat training, following a defeat by French marines (Carafano and Rodeback 2011).

2. Characteristics of the Pirate Mothership

Modern piracy has adapted to the constrained range of skiffs by commandeering larger ships with range and supply capacity to continue their hostage and cargo ransom operations in blue water (Mwangura 2010). The larger and slower mother ships serve as multipurpose vessels. The first purpose is to get pirate personnel into deeper blue waters and wait for other ships. The larger ships generally can carry more personnel and supplies allowing pirates to stay longer at sea waiting for potential victims. In addition to the basic supplies (such as food and water), the mother ships also carry weapons, hook ladders and grappling hooks for the attack missions. (MSCHOA 2011) The second purpose of a mother ship is to serve as the command ship center for coordinating pirate attacks (MSCHOA 2011). Attacks generally involve launching smaller skiffs from the mothership to their target. The third purpose is to carry or tow the smaller skiffs out to sea for launching coordinated attacks on merchant ships (NATO January 2006).

The pirate motherships come in a variety of sizes (NATO January 2006). Depending on what they can commandeer, the mothership may vary from a deep sea fishing vessel to a vessel as large as a tanker (Figures 9 and 10).

Figure 9. “Commandeered Fishing Boat with Skiff in Tow” (NATO January 2006).

Figure 10. "Commandeered Tanker Converted to Mothership with Skiffs on Deck." (NATO January 2006). Using these large vessels as floating bases, coordinated attacks can be launched at a moment's notice with minimum planning.

II. NEEDS ANALYSIS

This project focuses on providing a cost effective solution set for improving the ability to identify and track pirates as well as dissemination of information to commercial vessels. The HOA AOR necessitates ISR capability that can cover hundreds of thousands of square miles of ocean. Fortunately, the Department of Defense (DoD) has many of the necessary tools available to take on this challenge. The analysis performed addresses capability gaps and concept of operations gaps identified during research and interviews with stakeholders as well as surveys from UAS operators from the HOA AOR. The Alexander Kossiakoff and William Sweet system engineering process was applied and a problem statement and set of user needs were developed (Kossiakoff and Sweet 2003).

A. PROBLEM STATEMENT

A near term solution was desired by stakeholders until planned maritime UAS ISR programs, such as the BAMS program, reach initial operational capability. The resulting capability improvement concept presented in this paper augments and supplements the current commercial and coalition maritime situation awareness needs by filling the capability gap of persistent counter-piracy ISR. Initial research and stakeholder meetings resulted in the following refined problem statement:

> Commercial ships are beset by pirates extending from the Suez Canal & Arabian Sea in the North to 78^0 East and 10^0 South in the Indian Ocean. Coalition forces need to locate and apprehend pirates prior to their engagement of commercial vessels in this vast area of operations. Coalition forces need an ISR capability to identify, characterize, track and support piracy interdiction operations over extended durations and distances.

B. RESEARCH QUESTIONS

The following research questions were addressed for this project:

- What capability gaps need to be addressed with respect to countering the pirate application of mother ships?
- Can formation and application of a system or family of systems comprised of existing or near term Intelligence, Surveillance, and Reconnaissance (ISR) as-

sets meet stakeholders' needs in countermining the pirate application of mother ships?

- What characteristics, signatures and patterns mark a pirate mother ship?
- What sensor payload requirements are needed to exploit the characteristics, signatures and patterns of pirate mother ships?

C. CAPABILITY GAPS

Since the 1990s piracy has been ongoing and international efforts have been pursued to halt the rising trend of piracy in the HOA AOR, and all of them have met with marginal success. The present international effort is Combined Task Force (CTF) 151, a coalition effort of the Combined Forces Maritime Component Commander/Commander US Naval Forces Central Command. CTF 151 maintains a multinational, multi-ship presence in the Gulf of Aden, Bab el Mandab, Red Sea, and the Somali Basin. While CTF 151 is well organized, its effectiveness is limited by the resources on hand to carry out operations. Each warship is limited by the range of its sensors and the reach of its helicopters. In 2008, the Suez Canal Authority reported 22,000 transits. The assets needed to provide protective escort for each vessel transiting the AOR are simply not available. Warships are also limited by the time lapse between receiving the calls for assistance by merchants under attack and their arrival as well as by the difficulty discerning pirates from fishing and coastal traffic. Pirates are not readily identifiable as pirates unless a weapon is brandished. Until that moment, they are regarded as fishermen. While airborne assets can travel over the HOAAOR expeditiously, the limitations on airborne search capabilities have been defined by the airborne assets and sensor packages. For example the P-3C Orion maritime patrol aircraft ETOS is three hours (Military P-3 2011) and the SH-60B ETOS is three to four hours (Leoni 2011). Also, these two assets have advanced surface search sensor suites, but most Coalition member air assets do not. AIS is an important tool to support identification and sorting out surface contacts. Identifying the remaining contacts depends on the limited number of assets in the area and their sensor suite capability. As stated above, most Coalition members do not have the appropriate sensor suite capabilities and the numbers are insufficient to efficiently deter piracy activities in the HOA (Abgar 2010) (U. N. Council 2010). Survey results of operaters indicated that a shortfall of ISR assets was available in the region and that a primary concern to effectively conducting counter piracy operations was a lack of maritime surface radar capability.

D. LIST OF ASSUMPTIONS

Assumptions for this project are based on the available resources and project scope.

- Assumption 1 - All pirate activities operate in a sea state of four or fewer.
- Assumption 2 - Shore and Sea-Based ISR assets are options.
- Assumption 3 - All analysis occurs off-board of the ISR platform.
- Assumption 4 - The project scope is limited to detecting, locating, classifying, identifying, tracking, and reporting on pirate activities only.
- Assumption 5 - The project scope is limited to the HOA AOR only and does not provide monitoring outside the designated area.
- Assumption 6 - Systems must be available by end of calendar year 2012.

E. REQUIREMENTS CAPABILITIES

The fishbone diagram shown in Figure 11, "Contributing Factors for Successful Pirate Attacks" succinctly captures many aspects of the piracy challenge in the HOA AOR on which this project is focused. Most importantly, it shows the expansive area of operations, limited intelligence, and short response opportunities. Commercial vessel vulnerabilities are of interest in some limited areas.

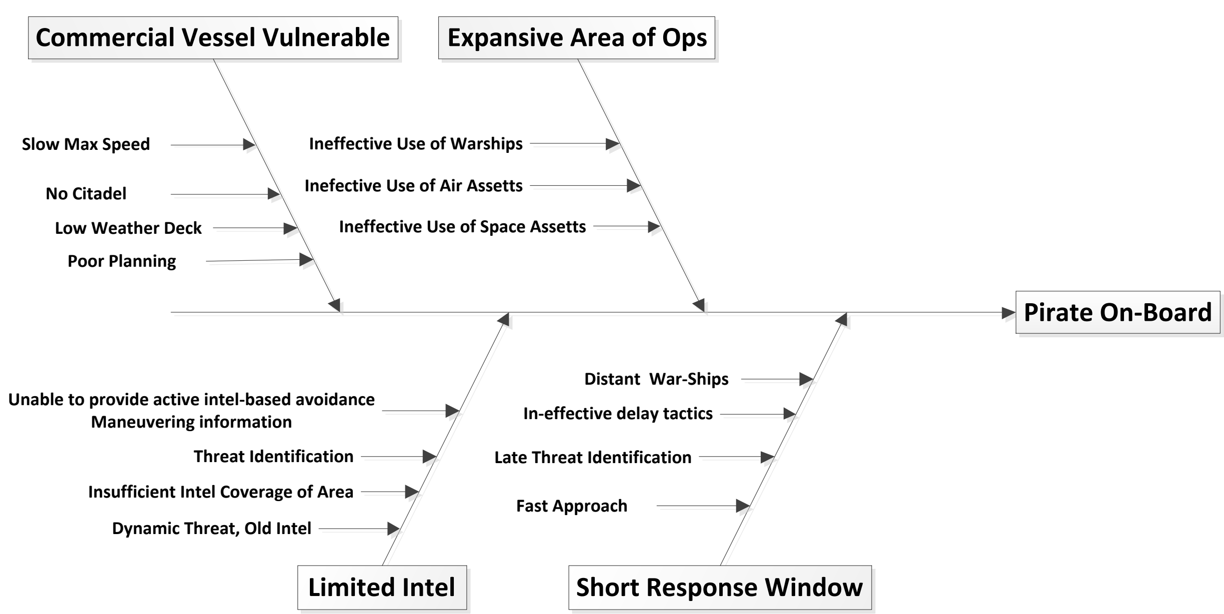

Figure 11. "Contributing Factors for Successful Pirate Attacks."

Early fact finding indicates that successful identification of pirates prior to conducting operations against a vessel should be a focus area. Response times of military ships after a vessel has signaled an attack are almost never less than the time required for pirates to seize a vessel. This is a function of the vast area the HOA AOR and limited resources of Coalition Forces.

The piracy threat zone, roughly 2.5 million square miles, sets the stage for a high endurance vehicle requirement. It also drives the need for high scan rates with wide angle or field of regard sensor suites. While the sensors payloads must support the scan rates of wide field, there must also be the ability to address the issues identified in the intelligence branch of the fishbone diagram. A capability must exist to distinguish friend from foe, fisherman from pirate, and mother ship from dhow or freighter. These challenges are diametrically opposed, with both the need for wide area scanning and focused detailed assessment. The short response window highlights the criticality of time and the constraints it imposes. This, coupled with the large area of operations, makes it clear that once an attack commences, it is most likely too late for naval forces to interdict the pirate ship. The time constraint indicates that a necessary capability is to provide useful information prior to the commencement of an attack.

The capabilities needed based on research and the initial problem statements are stated in Table 4, "Statements of User Needs." An effective and efficient Concept of Operations employing an existing system must deliver capabilities to fulfill the user needs.

Refined Need: Detect & Locate Mother Ship {Coalition Forces need to detect & locate Pirate Mother Ships prior to their engagement of commercial vessels}
Refined Need: Classify Identify Track {Coalition forces need to classify, identify, and track Pirate Mother Ships within the area of interest over extended durations and distance}
Refined Need: Communications {Communicate with Command and Control}

Table 4. "Statements of User Needs."

F. MEASURES OF EFFECTIVENESS AND PERFORMANCE

Each one of the operational needs have associated MOE parameters. This project assesses the effectiveness of using UASs for deployment to the HOA AOR to conduct operations described in the operational architecture description. The MOEs provide a basis for moving forward into the concept exploration phase where several options or UAS alternatives are explored and analyzed. MOE parameters for each of the above three operational needs are defined below:

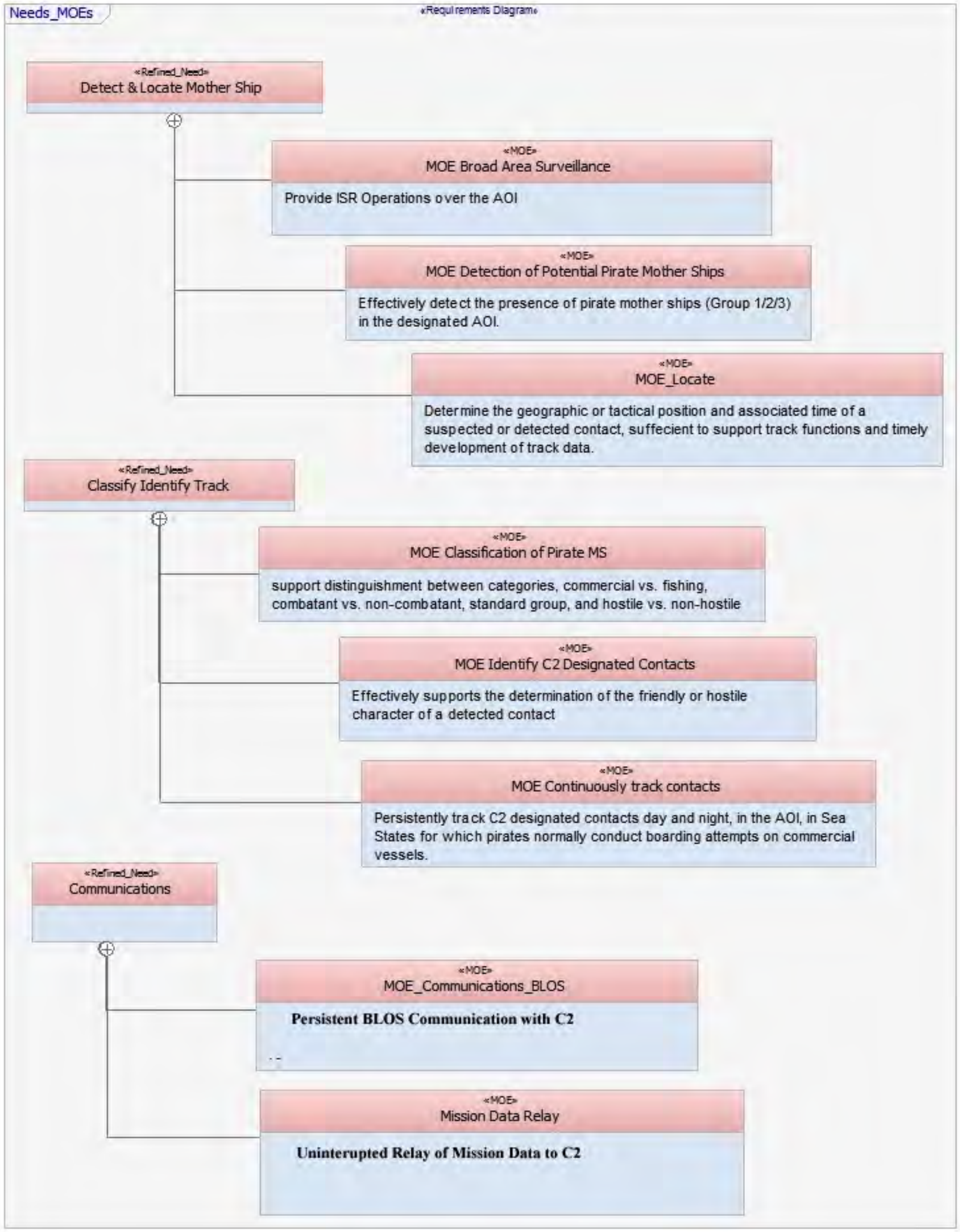

Figure 12. “Needs Mapped to Measures of Effectiveness.”

A stakeholder need prioritization scheme was used to determine the importance of each of the MOE. MOE are mapped to MOP by using a set of QFD matrices. Table 5 summarizes the MOP defined for the PMSW&RS project.

Measure of Effectiveness (MOE)	Measure of Performance (MOP)	Threshold	Objective
Detection of potential pirate mother ships	Detection a target at 25m^2 radar cross section, 20kft above MSL minimum, at level flight attitude-360 degrees	80 nmi	200 nmi
Locate pirate mother ships	Locate: at25m^2 radar cross section, 20kft above MSL- minimum, at level flight attitude-360 degrees, Radial Position	500 Ft	200 Ft
Communications LOS	V/UHF Communications Package	Yes	Yes
Communication BLOS	BLOS Capability Only	Yes	Yes
Track Multiple Simultaneous Targets	Track Multiple Simultaneous Targets at 20Ft above MSL, 360 degrees, 25m^2 RCS	150 Contacts	200 Contacts
Classification & Identification	IR and visual imagery at 20,000 ft, clear day	NIIRS 7	NIIRS 8
Broad Area Surveillance	Airspeed	80 Knots	200 Knots
	Endurance at radius of 600 nmi (time on station)	12 hrs	24 hrs

Table 5. “Measures of Performance and Effectiveness.”

III. CONCEPT EXPLORATION

A. INITIAL CONCEPT WORK

Initial research conducted during the needs analysis phase of the project resulted in the PMSW&RS operational concept to employ UAS off the Horn of Africa. The UAS would be used to conduct intelligence, surveillance and reconnaissance missions in order to provide advanced warning to commercial ships and support maritime domain situational awareness. The operation is broken down into two primary mission areas, Figure 13 "Activity Mapping to Primary Mission Area." Mission Area 1 is associated with broad area detection, location, communication and data relay, as well as broad area tracking functions. Mission Area 2 is associated with classification and identification functions. Two concepts were examined with allocation of mission areas being the primary difference.

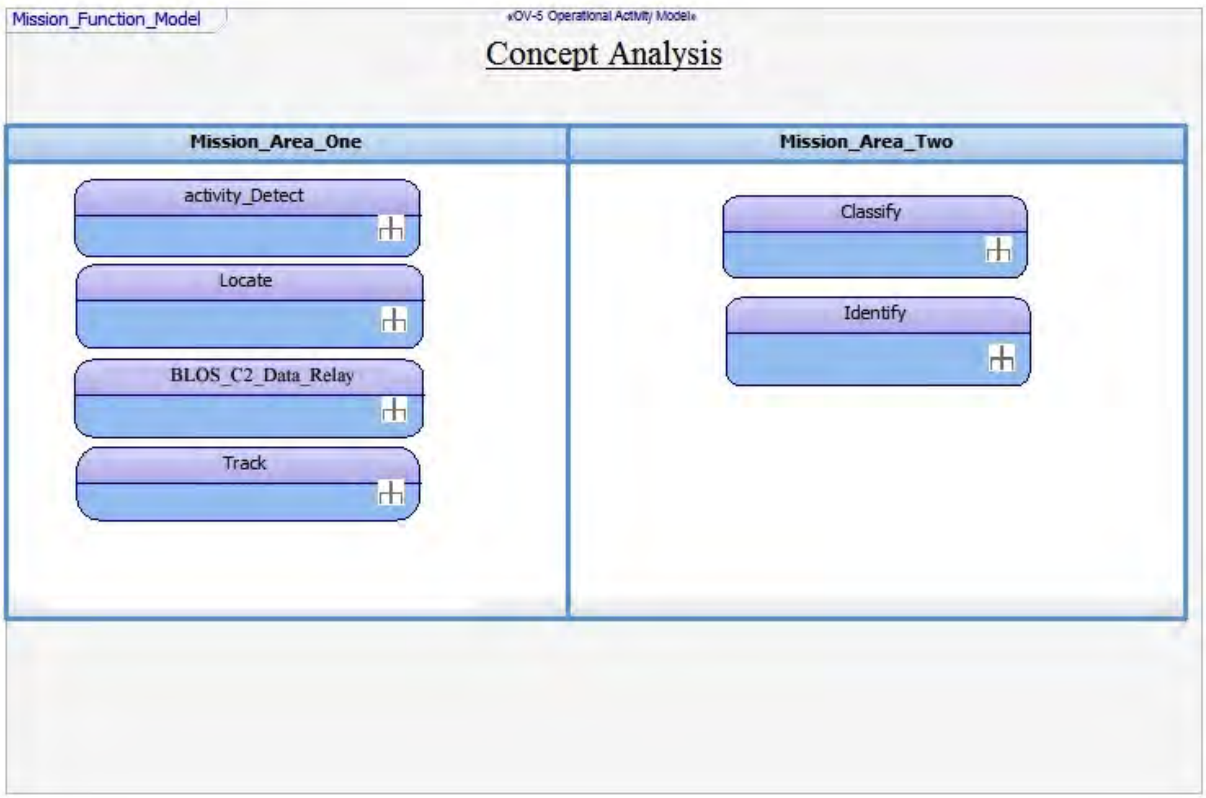

Figure 13. "Activity Mapping to Primary Mission Area."

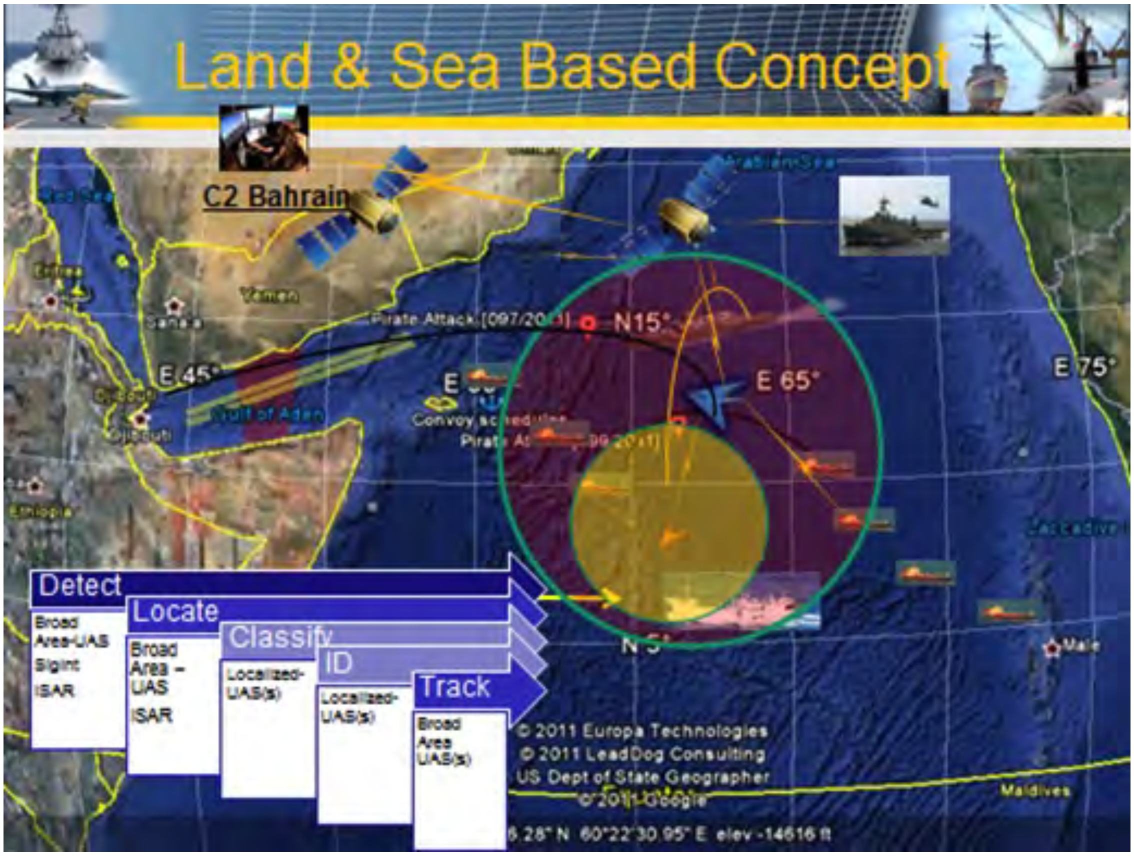

Figure 14. "Concept I."

1. Concept I

UASs are deployed from the Horn of Africa area airfields (in this concept graphic, Africa) which proceed to an area of interest designated by operational commanders. Upon arriving in the area of operations, the UAS begins to conduct broad area detection and location functions. The Mission Area 1 UAS is equipped with an AIS receiver and utilizes onboard systems to filter out targets that are not of interest. The Mission Area 1 UAS has the ability to support communications and data relay so as to facilitate communications over V/UHF with C2. In addition, the UAS supports data relay for command and control of smaller UASs. Upon detection and location of targets of interest, a Mission Area 2 UAS is dispatched to conduct classification and identification activities. The Mission Area 2 UAS would be a smaller ship-based UAS with electro-optical camera to provide imagery for classification and identification. Tracking would be conducted by the larger land-based UAS with maritime radar.

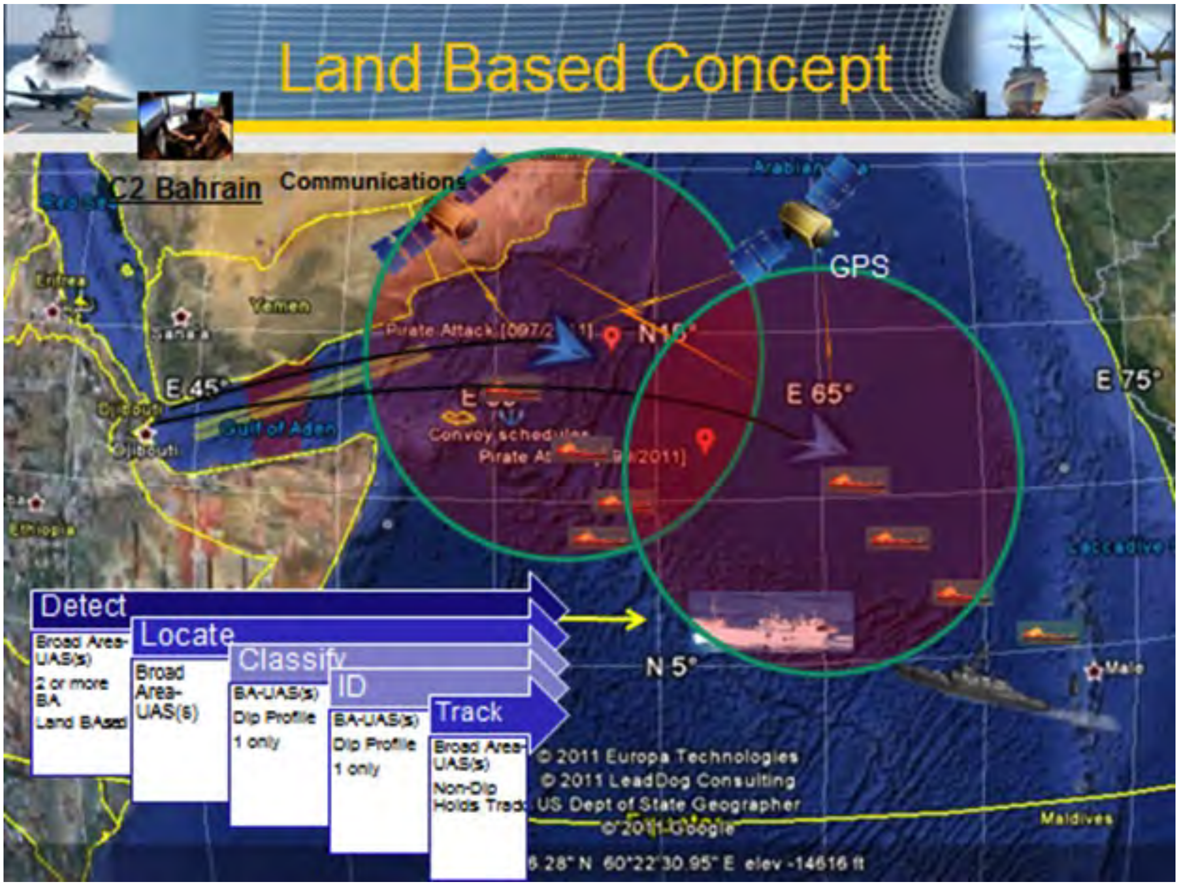

Figure 15. "Concept II."

2. Concept II

A medium altitude UAS performs operations for both Mission Area 1 and Mission Area 2 from a land base. Analysis of this concept focused on the benefits of increased airspeed as well as the sensor capabilities available in land based UASs. Specific consideration was given to the capabilities offered by the Electro-Optical/Infrared sensors found on the larger UASs to determine the altitude for which classification and identification is possible.

B. CONCEPT REVIEW

Both of the concepts outlined above were shared with stakeholders and the primary concerns expressed revolved around Concept I and the availability of the ship-based UAS. The following concerns were raised by stakeholders:

- Many of the ship based UASs operated today are "pay for service" agreements in which contractor teams deploy aboard U.S. Navy Ships.
- Concept I Concept of Operations would involve the U.S. ship remaining in a single, central area of operations and preclude it from conducting other missions in order to effectively support the concept.
- Many ships would lose capability in other war fighting domains to support piracy operations.
- The opportunity cost of allocating an expensive naval vessel.
- Communications relay and the danger that the communications relay and link chain could be compromised.

There were two primary concerns on Concept II, and both were common with Concept I:

- Lack of locations for forward operating bases
- Proximity to the HOA AOR area of interest.

While the challenges associated with Concept II are not insignificant, research indicates that they can be overcome with existing UAS platforms. Concept I presents a far more complicated and more costly effort. The smaller UASs are significantly cheaper, but the allocation of the naval vessel with its crew outweighs the savings of the smaller vessel. Concept II offers the best basis for a formulation of successful operational concept. Further, interviews with experts indicated that the EO/IR pod found on several current land-based UASs has the capability to support classification and identification at altitudes in excess of twenty thousand feet above mean sea level.

Interviews with Navy Reaper operators provided an example of successful operations of land-based UASs from the Seychelles in support of counter piracy operations. Further research has identified two other potential forward operating bases, Fujairah (FJR), United Arab Emirates (UAE) and Malè, Maldives (Figure 16, "UAS FOBs.") The potential candidates have locations within a 600 mile radius of the areas of interest in the HOA AOR, a distance that the team determined was acceptable for the mission.

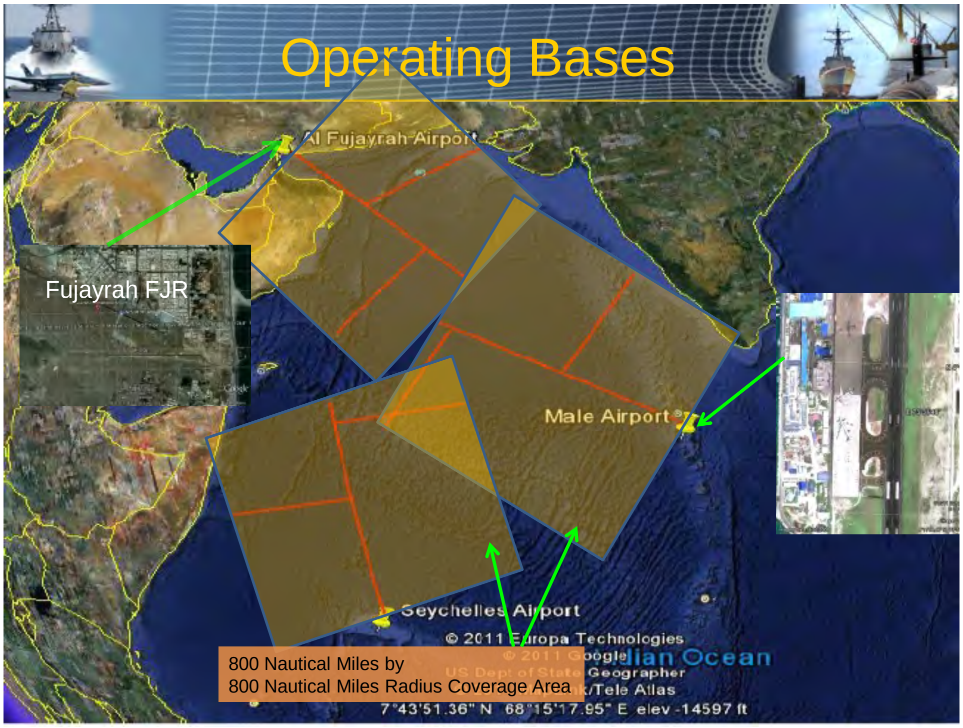

Figure 16. “UAS FOBs.” Potential UAS Forward Operating Bases: Fujairah UAE, Male, Maldives, and Seychelles Airport.

C. PMSW&RS CONCEPT OF OPERATIONS

The refined operational concept is presented in the OV-1 (Figure 17, "OV-1). The concept relies on a land-based UAS approach utilizing forward operating bases. Land-based UASs are deployed from HOA AOR area airfields and proceed to an area of interest designated by operational commanders. Upon arriving in the area of operations, the UAS will begin to conduct the mission area activities previously described.

Figure 17. "OV-1." (Google.com 2011).

D. ARCHITECTURE DEVELOPMENT AND ANALYSIS

The operational architecture of the PMSW&RS has been developed after the careful consideration of user needs, problem space, capability gaps, market analysis, environmental analysis, and stakeholder surveys. Operational interfaces or nodes required to complete the antipiracy mission are identified in Figure 18, "Operational Nodes Diagram" and are described in Section D, "Architecture Development and Analysis: Operational Nodes and Operational Activities."

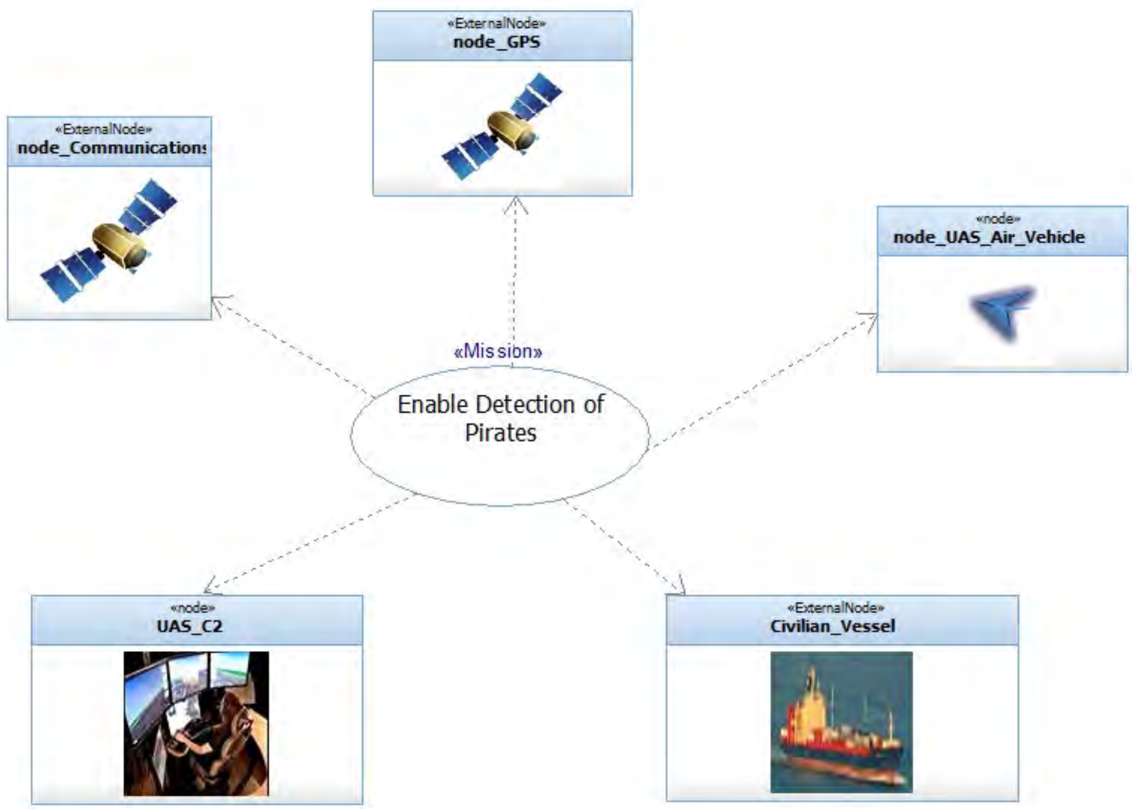

Figure18. **"**Operational Nodes Diagram."

1. Operational Nodes

a. Communications Satellite

Satellite coverage provides the vital capability for Beyond Line of Sight communications. The continuous communications coverage would provide UAS control, voice, data and video used to combat piracy in the Horn of Africa and surrounding areas.

b. GPS Satellite Analysis

Geospatial information is critical to locating not only the pirate ships but also for command and control of the vehicle beyond the horizon.

c. Commerical Vessel Analysis

Commercial ships greater than 300 tons should be broadcasting AIS in accordance with international guidance, and the UAS system will receive AIS data broadcasted from the ship.

d. Command and Control Analysis

Command and Control (C2) is depicted separate from the unmanned aerial vehicle (UAV). This helps in the modeling effort to show communications between the UAV and C2.

e. Unmanned Aerial Vehicle

The UAV is the platform for delivering sensor capabilities, intelligence collection and beyond-line-of-sight communications. The UAV utilizes onboard systems to filter contacts that are not of interest. The UAV will receive mission data and send sensor data from command and control. Upon detection and location of contacts of interest, classification and identification activities are performed. Command and control will verify the classification of vessels that are tagged as potential pirates by the UAS. The UAV will collect speed, heading and coordinate information on vessels identified as threats.

2. Operational Activities

The operational activity model (Figure 19, "UAS Operational Activity Model, Orthogonal View") shows the operational activities of the architecture for the counter-piracy operation. It consists of six operational activities for the UAS that include detect, locate, classify, identify, track and transmit data. It is a trace-or-sequence diagram that captures the messages and general timing of communications and events that would occur during the counter piracy mission.

In this sequence, a UAS platform is deployed to an operational area to conduct piracy detection operations. Early messages and data transfers highlight the importance of the communications and GPS satellite infrastructure while the latter or lower portion of the sequence diagram captures the details of the on-scene mission. The Satellite link is clearly the critical node in this system, as all operational activities depend on a continued link. AIS is a fundamental element in this concept as it is a primary filter utility. The first decision point in Figure , represents the application of filters to include the use AIS filters.

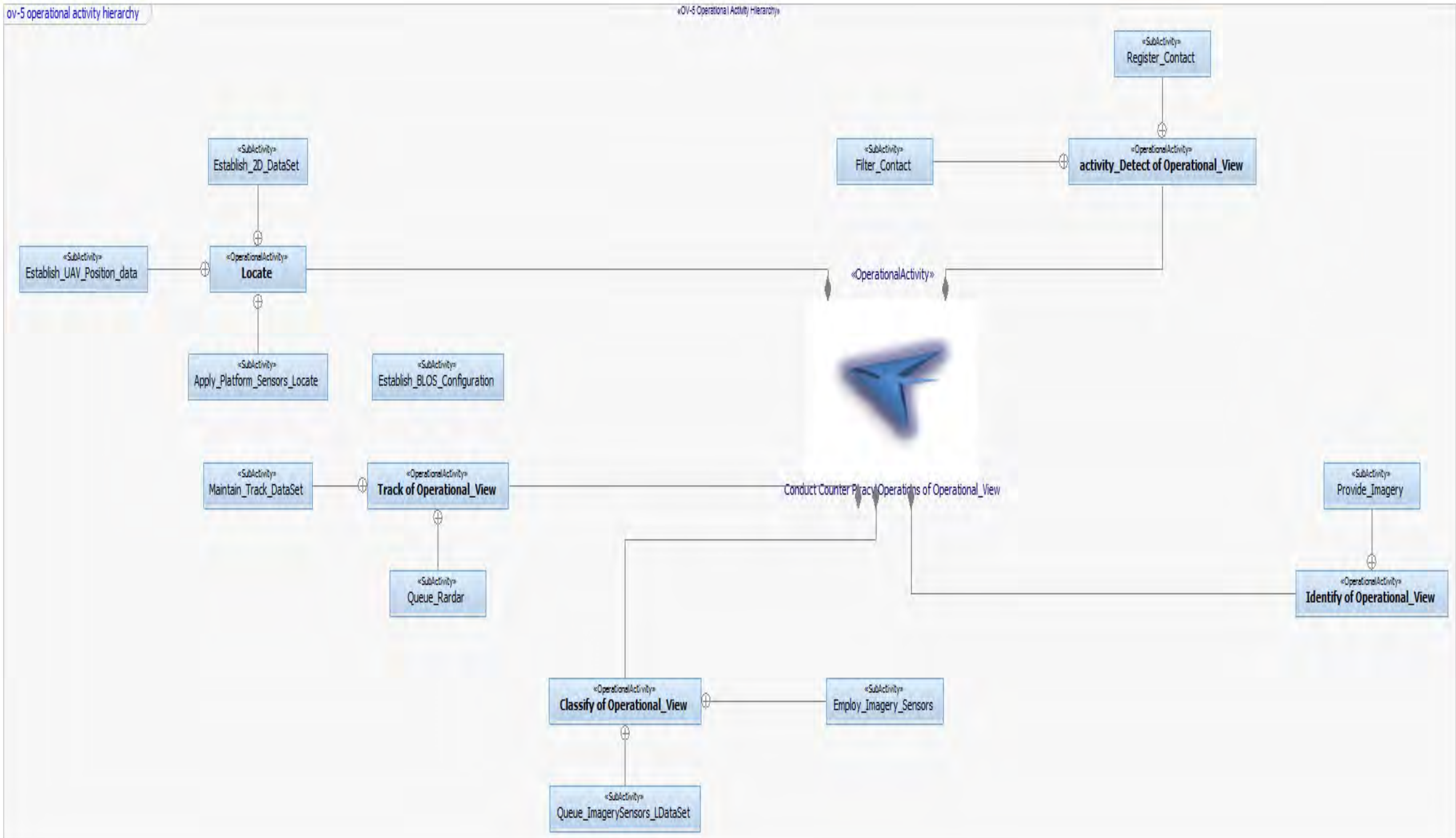

Figure 19. "UAS Operational Activity Model, Orthogonal View."

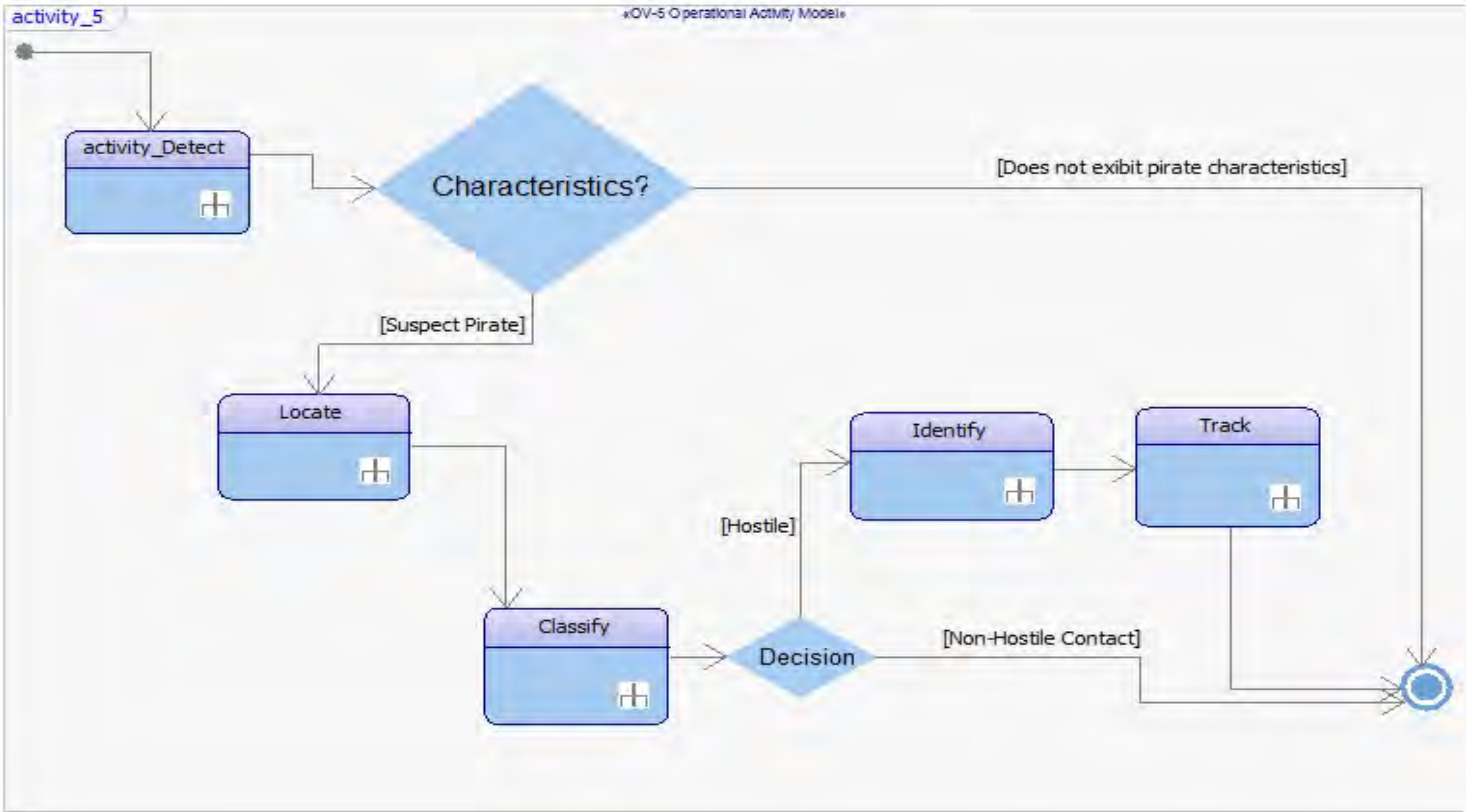

Figure 20. "OV-5."

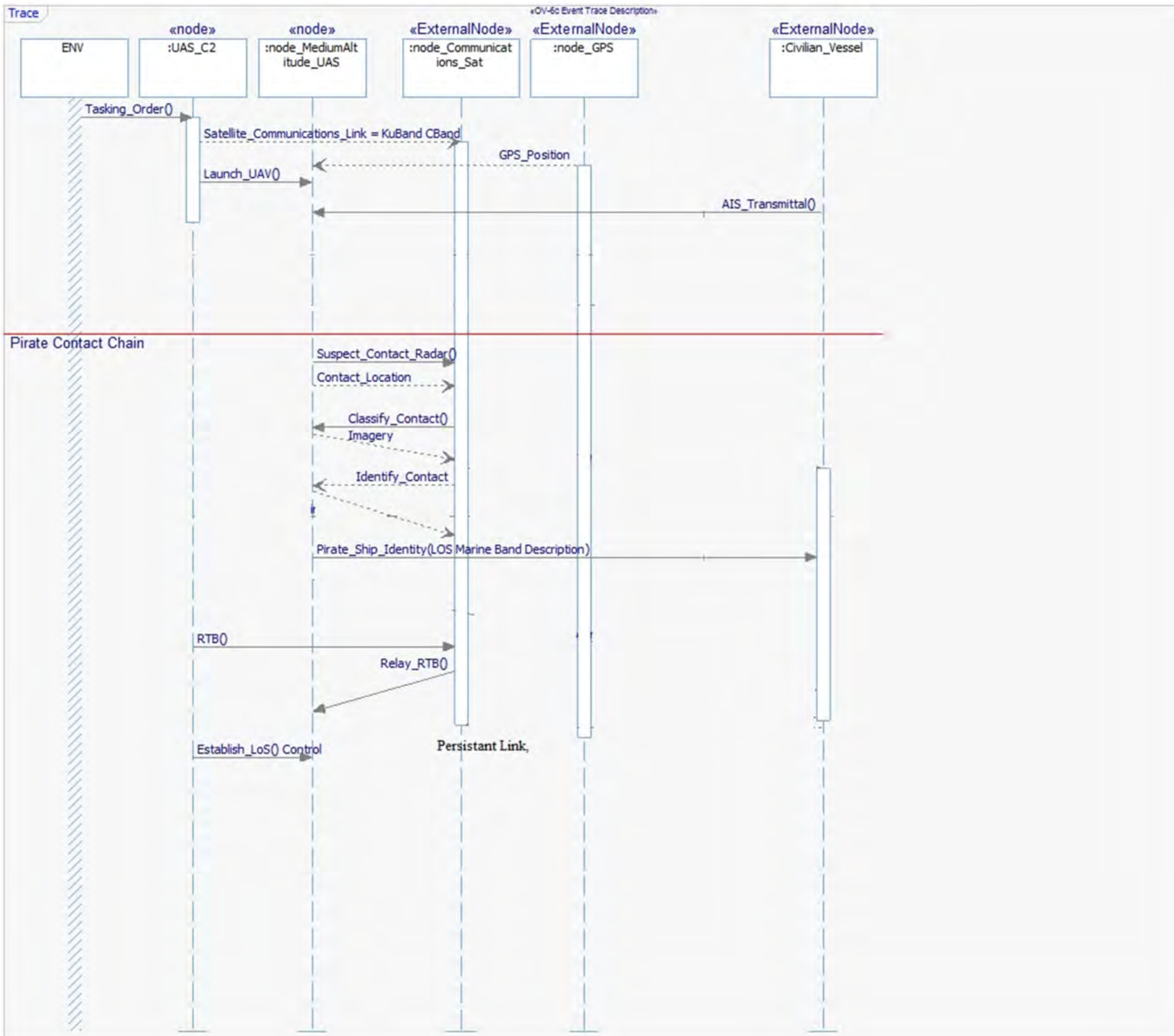

Figure 21. “OV-6c Event Trace Descriptions.”

In this sequence diagram, in order for useful data to be collected on radar contacts, the current and correct coordinate location of the UAV must be determined and updated continuously. Detection of a contact of interest triggers the classification tasking and identification activities. Imagery data supports classification and identification activities. Classification of a probable pirate ship results identity activities. Maritime V/UHF from the UAS carries the broadcast warning. A return to base message from C2 signifies the completion of operations. When the UAV is within LOS of its landing field, then LOS communications will be established with the UAS for landing.

3. Concept Exploration and Tradeoffs

Early evaluation of simulation factors (Appendix F: "Modelling Using Excel Software") indicated time, specifically the short time between when the pirate enters the HOA AOR and when the pirate mother ship is able to use radar or AIS to detect and locate a target commercial vessel is important. The system has to detect potential threats and identify friend or foe before this point to allow time for reaching a decision about information transmission and time needed for merchant vessels to react.

On the principle that it is desirable that a pirate ship not be allowed to sight a commercial vessel before C2 sends out a message warning of its presence, our objective is to enable C2 to issue a warning before the pirate vessel closes within the line of sight distance.

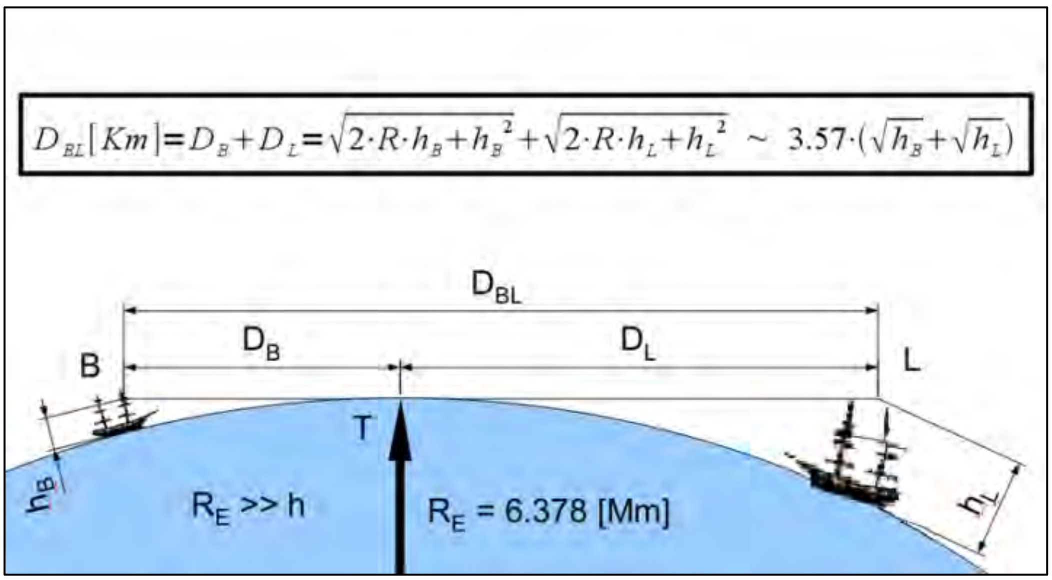

Figure 22. "Line of Sight Equation."

Pirate motherships would be using either an onboard AIS system or radar system that would only be able to detect targets at a maximum range of their radar's line of sight range from its antenna located on its mast to a merchant ship's antenna on its mast (Figure 22, "Line of Sight Equation,"(Aviation Department NAVAIR-4.5 1999)). A conservative approach was taken by using a mothership with an approximate hull height of 60 ft and a mast of 150 ft to detect similarly sized commercial ships transmitting AIS at a maximum range of 103 miles.

A successful system needs to detect at least 80% of all pirate mother ships (MOE, Detection) and warn commercial vessels before they are within the 103 mile range. Earlier detection allows for more time to perform classification and identification functions and should be considered when developing program technical performance measures.

UASs have defined speeds and sensor fields of view that determine how often a specific area is scanned. Scanning needs to be frequent enough to detect threats when they cross into the AOI. If the area is not scanned frequently enough, the probability of system success will fall below the threshold level of detection.

Requirement tradeoffs and evaluations were necessary to determine how many UASs will be essential to yield the desired detection rate. A key parameter necessary to begin analysis was determination of control zone size and configuration. Examination started with analysis of plots of pirate attack density found on multiple websites, to include the website for Maritime Security Horn of Africa (MSCHOA) (MSCHOA 2011) (Figure 11, "Contributing Factors for Successful Pirate Attacks"). Results of zone analysis focused on protecting sea lanes in order to maximize effectiveness. Zone determination information can be found in Appendix F, "Modelling Using Excel Software." Zone analysis was done using a Microsoft Excel model. The output of the model is shown in Figure 38, "Sensitivity Analysis (Detection Accuracy Range," with the percentage of motherships that are successfully detected before they reach the required warning distance from commercial vessels traveling through the center of our protection zone.

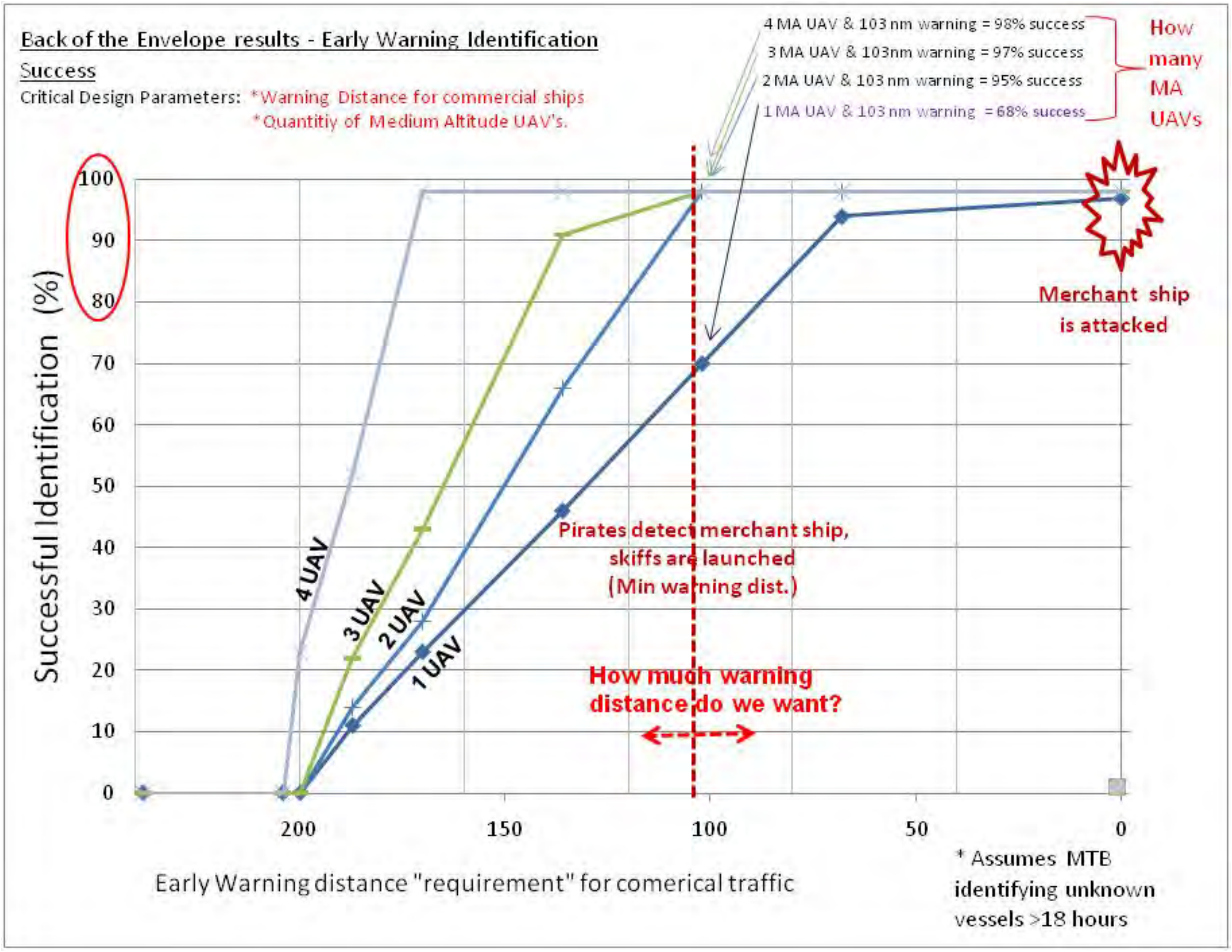

Figure 23. “UAS Early Identification & Warning.”

As the required warning distance is increased, the time allowed for each Medium Altitude UAS to scan, identify, and track each ship is reduced. When pirate ships start attacking at a faster rate than there are UASs available to complete their tasks, the successful detection rate will be reduced. The analysis indicates that at least two medium altitude UASs are required given the constraints of readily available military off-the-shelf hardware performance parameters. If a single UAS is used, then all of the contacts detected cannot be identified because the entire area of interest cannot be successfully covered in a reasonable time. This is again due to the situation where a pirate enters the area of interest and a single UAS cannot re-scan areas before a pirate makes it to the minimum distance required to warn the commercial ships. Two or more UASs give sufficient coverage of the entire area of interest, so no pirate goes unidentified prior to reaching the minimum distance that would allow the commercial ship to evade attack. Further, the results indicate that 120 nautical miles warning time can reasonably be achieved when using only two UASs and meeting the threshold of 80% detection success.

4. Sensitivity Analysis

To determine which system requirements have the biggest impact on the overall System MOE, successful detection rate, a sensitivity analysis of the following factors was performed:

- UAS Speed
- UAS Endurance
- UAS Radar Range

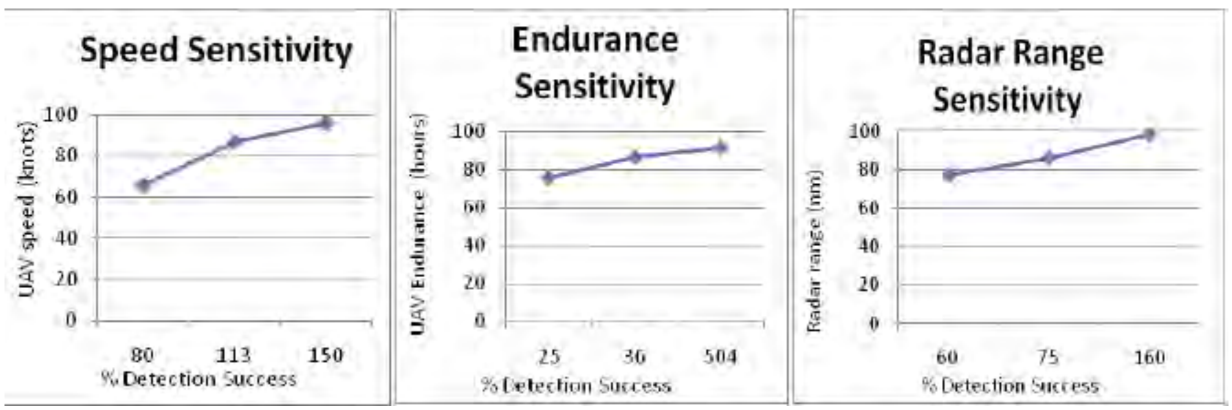

Figure 24.“Sensitivity Analysis.”

Using high, medium and low levels of each UAS requirement, it is apparent that the UAS speed has the highest impact to successful detection MOE, followed by the on-board radar range. This is demonstrates the importance of quickly and repeatedly scanning the zone of interest for pirate ships before the pirate has time to travel to a merchant ship. With greater speed, the UAS can traverse its flight path in a shorter time with a wider radar range, so the UAS would need to travel less distance to scan the entire zone. The sensitivity analysis results reinforce the simulation that the fastest UAS with the widest radar range outperformed all other UAS platforms in the system MOPs.

E. MARKET SURVEY

Market research was conducted over a six-month period, focused on existing technologies and application to the concepts. The objective of the research was to identify systems which could remain on station in the HOA AOR for as long as possible and have the right radar and optical systems without exceeding the UAS's payload weight limit.

The most challenging aspects of the requirement set were the detection of sea surface vessels and the tracking of these contacts once found. It appeared that there was a great amount of technology development underway for surface-to-air and surface-to-ground ISR. The most significant challenge for researched systems was finding and classifying small to medium sized vessels accurately (Shaver 2011). This shortfall in capability supports the continued tradeoffs between high altitude search and low altitude surveillance.

1. Candidate Unmanned Aerial Systems

Many UASs were investigated to find the right solution for the original and modified concepts. The most capable UASs for this application were the Heron TP, Guardian and the LEMV systems. These three UASs were used for the later portion of the system development and modeling.

System Name	Type of UAV	Developer	Maturity
Heron TP (EiTan) UAV*	Long-Endurance Medium-High Altitude	IAI / Malat	First flight on 15 July 2006, Currently in Service
MQ-9B Guardian UAV* (Variant of MQ-9 Reaper)	Long-endurance, Medium-High Altitude	General Atomics	Over-water developmental test February 2010
Long Endurance Multi Intelligence Vehicle (LEMV)*	Very Long-endurance, High-Altitude	Northrop-Grumman	OT&E Scheduled early 2012
MQ-4C BAMS UAS (Variant of Global Hawk)	Broad Area Maritime Surveillance, Long-endurance, High-Altitude	Northrop-Grumman	CDR on March 7, 2011, First flight Schedule. 2012, Op Capable Schedule. 2016
MQ-9 Reaper	long endurance, medium-to-high altitude	General Atomics	First flight on February 2001, Currently in Service
Scan Eagle Mini UAV	medium endurance, Low to medium-altitude	Boeing Corp	First delivery to US Navy in 2005, Currently in Service
MQ-8B Fire Scout	Low endurance, Low to medium-altitude	Northrop-Grumman	First deployment aboard a US Navy ship December 2008, Currently in Service

Table 6. "UAS Platforms Researched."

This refined list of systems included acceptable ISR capabilities for maritime surveillance. The maritime environment has unique ISR challenges due to the continuous motion of the background and the higher the sea state so the greater this challenge.

a. Maritime Radar Sensors

Many types of sensor systems were researched to find the ones that would perform well enough on a sea surface environment. The primary sensor systems of interest are:

- Inverse synthetic aperture radar (ISAR)-maritime with Moving Target Indicator
- Electro-Optical/Infrared Sensors
- Signal Intelligence Suite

The ISAR is preferred over the SAR radar for maritime imaging and target recognition. Not only is the target moving as it sails, but there are also movement characteristics produced by the motion of the ocean (ship pitching and rolling). Using the ISAR radar also allows the achievement of image resolutions of a much bigger antenna. The ISAR allows good image resolution at greater distances. The payload restrictions of UASs and the nature of the targets that will be imaged in a sea environment make the ISAR a necessary component of any broad area maritime ISR system. EO/IR for day and night imagery in support of classification and identification is critical for this mission. SIGINT is an additional capability that while not critical to mission success would help support the full mission spectrum.

System Name	Type of System	Developer	Maturity
Vehicle And Dismount Exploitation Radar (VADER)	SAR	Northrop Grumman	15 July 2008 First Flight
EL/M-2022	Maritime Surveillance RADAR	Elta Systems	Mature
MX-20	Airborne Electro Optic	L-3 Technologies	Mature
SeaVue™	X-band Maritime surveillance Radar	Raytheon	Initial Flight Test in 2011
Multispectral Targeting System A (MTS-A)	Multispectral Targeting System	Raytheon	Prototype OT&E in 2002
Multispectral Targeting System B (MTS-B)	Multispectral Targeting System (hi-altitude)	Raytheon	LRIP in 2004

Table 7. "Sensor Systems Researched."

2. Unsuitable Candidate Unmanned Air Vehicles

There were a number of systems that were evaluated that did not meet the needs and requirements defined for our system. Listed below are a few of those platforms and some of the reasons for rejecting them as part of our system.

a. Scan Eagle

Figure 25. “Scan Eagle Image.”

The Scan Eagle is a small to medium altitude reconnaissance, surveillance and target acquisition UAS developed by Boeing, Inc., that entered service in 2004. It uses a launch and recovery system that allows it to operate without the need for an airfield. The payload includes a real time color electro-optical camera and an infrared camera for night operations. It can track both stationary and moving targets due to it is built-in gimbaled system and can provide low altitude persistent surveillance.

Scan Eagle Specification	
Power Plant:	3W 2-stroke piston engine; 1.5 horsepower
Wingspan:	10.2 feet (3.1 meters)
Length:	3.9 feet (1.19 meters)
Weight:	39.7 lbs (18 kilograms)
Speed:	55-80 mph
Endurance:	20 + hours
Operating Altitude:	16,000 feet air ground level (4,876 meters)
System Cost:	approximately $3.2 million (2006 dollars)
ISR Payload:	High resolution, day/night camera and thermal imager

Table 8. “Scan Eagle Specifications.”

In 2005, the system was modified for use on United States Navy high-speed vessels. The modification allowed the system to be ship-launched and recoverable, aided by an on-ship GPS beacon. The system provides real time intelligence and situational awareness. It can remain on station for up to 15 hours. The aircraft has a payload bay that allows it to be configured for unique operations. The system can run autonomously to a location of interest or receive operator inputs using a GPS and onboard flight-control system. The analysis of alternatives pointed away from a high altitude scan – “identify and track” coupled with a low altitude identification/classification approach towards one where a medium altitude system would perform all system functions. The departure from a high and low altitude concept led to the Scan Eagle being discounted as a viable solution (U.S. Air Force 2009).

b. MQ-4C Broad Area Maritime Surveillance (BAMS) UAS

Figure 26. "Broad Area Maritime Surveillance (BAMS) Image."

The BAMS UAS is based on the proven Global Hawk unmanned aircraft system specifically modified for persistent maritime ISR. It can operate twenty-four hours a day, seven days a week with an 80% ETOS. It is designed to operate at an altitude of 40,000 feet above air traffic and weather. It can operate up to 3,000 miles from its launch point and stay on station for 26 hours (Unmanned Editor 2011).

It is equipped with various sensor systems, including a multi-function active sensor Active Electronically Scanned Array (AESA) X-band radar that can detect and classify at long range. It also uses the Multi-Spectral Targeting System-B (MTS-B) Electro-Optical and Infra-Red (EO/IR) system, giving high-resolution images and video for target tracking. It has an AIS system for monitoring transponders of maritime vessels for initial identification in high traffic areas.

MQ-4C BAMS Specifications	
Wingspan	130.9 ft (39.9 m)
Length	47.6 ft (14.5 m)
Height	15.4 ft (4.6 m)
Gross Take-off Weight	32,250 lbs. (14,628 kg)
Max. Internal Payload	3,200 lbs. (1,452 kg)
Max. External Payload	2,400 lbs. (1,089 kg)
Self-Deploy	8,200 nm (15,186 km)
Max. Altitude	56,500 ft (17.22 km)
Max. Velocity	331 knots True Air Speed (TAS)
Max. Endurance	28 hours

Table 9. "MQ-4C BAMS Global Hawk Specifications."

The BAMS UAS was not selected as a candidate vehicle for the system due to the current state of maturity. It was deemed that the risk was too great that it would not be operational within the requisite timeframe. Another factor was the possible unavailability of the system once it was operational. Research revealed that it would be highly unlikely to be able to procure the BAMS vehicle. All the scheduled deliveries were allocated to different programs. The BAMS UAS is scheduled to be operation capable in 2016. (Unmanned Editor 2011)

c. MQ-8B Fire Scout

Figure 27. “Fire Scout Image.”

The Fire Scout UAS is a rotary wing autonomous helicopter designed for vertical take-off and landing allowing it to provide situational awareness and targeting support in combat. In 2001, the Fire Scout program was cancelled by the United States Navy because it did not meet their needs. The system was improved under a United States Army contract leading to the MQ-8B configuration with enhanced capabilities. Improvements allowed the Fire Scout to perform its role in the air, on land and at sea. In 2006, the MQ-8B was the first autonomous helicopter to land on a moving ship at sea as part of its operational requirements. The system now can integrate various modular payloads to include Tactical Synthetic Aperture Radar (TSAR) with moving target indicator, multispectral sensor and Signal Intelligence (SIGINT) can be added for beyond-line-of-sight (BLOS) targeting. This system was discounted early on as a viable solution for our system because of low endurance (Northrop-Grumman 2011).

MQ-8B Fire Scout Specifications	
Power Plant	Rolls-Royce/Allison 250-C20W turbo shaft; 310 kW (420 shp)
Length	23.95 ft
Rotor Diameter	27.5 ft
Height	9.71 ft
Empty Weight	2,073 lbs.
Gross takeoff Weight	500 – 3,150 lbs.
Payload weight	700 lbs.
Service Ceiling	20,000 ft
Max. Speed	115 knots
Cruise Speed	110 Knots
Combat Radius	110 nm
Endurance	8 hrs.
Time on Station	5 hrs

Table 10.“MQ-8B Fire Scout Specifications.” (Northrop-Grumman 2011)

3. Suitable Candidate Unmanned Air Vehicles

Three platforms were selected for the analysis of alternatives. The platform selection was based on the medium altitude and high endurance operational concept. There were a number of UASs that did meet the needs and requirements of the project. To meet the mission requirements, the vehicle needed an effective sensor suite, long endurance and ability to provide continuous monitoring to find and track potential threats. The vehicle also needed to have adequate loitering speed to cover the area under patrol. Too long between scanning of any area could result in pirates evading the patrol area thus reducing the effectiveness of the system.

a. *Heron TP*

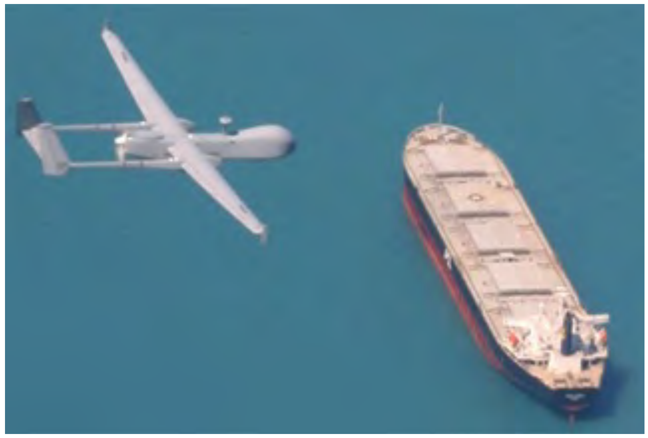

Figure 28. "Heron TP Image."

The Heron TP, Figure 28 and Table 11, is a high-altitude reconnaissance and surveillance UAS developed by Israel Aerospace Industries (IAI). Entering service in 2008, it is the second generation vehicle produced for the Israel Air Force, the Indian Ministry of Defense and the Turkish Air Force. It has a wingspan of twenty six meters, making it one of the largest UASs. It has an operating ceiling of 45,000 feet and can loiter at the area of interest for up to thirty six hours.

Heron TP Specifications	
Engine	Turbo-Prop
Power	1,200 hp
Propeller diameter	9.2 ft
Max Take-off weight	10,230 lbs.
Max. Payload capacity	2200 lbs.
Max. Fuel capacity	3850 lbs.
Total length	46 ft
Wing span	85.3 ft
Total height	10.8 ft
TO Distance	<3281 ft
Maximum altitude	> 45,000 ft
Operational Altitude	> 41,000 ft
Time of climb to OA	< 40 min.
Max. payload weight	> 990 lbs.
Max. speed	220 ktas at 45 Kft
Cruise speed at OA	180 to 200 ktas
Total mission time	>24 h
Loiter time at 550 NM	> 16 h
Loiter time at 800 NM	> 12 h

Table 11. "IAI Heron TP Specifications."

The Heron TP has a direct line-of-site data link system as well as an airborne data relay for beyond line-of-sight operations using SATCOM. This UAS has the capability to operate day or night and in all weather conditions. Available payloads include EO/IR/LRF, SAR, a medium power RADAR (MPR), ELINT, and COMINT packages for beyond line of site real time data transmissions (Israel-Weapons.com 2011).

b. Long Endurance Mult-Intelligence Vehicle (LEMV)

Figure 29. “LEMV Image.”

The LEMV, Figure 29 and Table 12, is a high altitude very long endurance ISR system that employs a hybrid air vehicle (HAV) configuration. It is designed to operate runway independent due to its short runway launch capability with excellent ground stability. It uses aerodynamic lift during takeoff and then uses helium during flight. The LEMV is made of a combination of Vectran, Kevlar and Mylar giving it the capability to withstand and survive small arms fire.

LEMV Characteristics	
Power Plant:	four diesel engines and a vector vane technology
Fuel Capacity	18,000 lbs.
Fuel Consumption	10X less than comparable capability vehicles
Length:	302 feet
Height	84 feet
Max Speed:	80 kts
Loiter Speed	30 kts
Endurance:	21 Days
Operating Altitude:	> 22,000 ft. MSL
Range:	1,500nm – 2,400nm
Payload Volume	< 2,700 cu ft
Max Payload Capacity	15,000 lbs.
ISR Payload:	Radar, SIGINT, Full Motion Video, LOS/BLOS COMM Relay

Table 12. “LEMV Characteristics.”

The LEMV is designed to utilize twelve to twenty-four forward-deployed crew members in the support of eighteen vehicles. The vehicle will be able to stay on station for twenty-one continuous days with twenty-four hours of uninterrupted eyes-on-target. Northrop-Grumman used an open architecture design allowing for multiple configurations and the ability to incorporate future technologies (Northrop Grumman's LEMV Program Completes Three Major Milestones 2010). Operational costs will be low with a fuel cost of approximately $11,000 per twenty-one day deployment. The Northrop-Grumman LEMV is currently under development with a final acceptance test scheduled for December 2011. The vehicle will undergo a demonstration in an operational environment in early 2012.

The LEMV has all of the characteristics to meet the maritime ISR needs. Its unique twenty-one day continuous scan time-on-station provides a high probability of locating pirates in the area of interest (Northrop-Grumman 2011).

c. MQ-9B Guardian

Figure 30. “MQ-9 Guardian Image.”

The General Atomics MQ-9B Guardian UAS, Figure 30 and Table 13, is a maritime variant of the proven Predator B drone. The Predator B modifications include changes to the structure, avionics and incorporated communications enhancements. This UAS was designed for use by the United States Customs and Border Protection and the United States Coast Guard for maritime ISR for the detection of threats.

MQ-9B Guardian is equipped with the Raytheon AN/ASS-52 Multi-Spectral Targeting System (MTS-B). The MTS-B sensor uses the three-to-five micron infrared band that assists in penetrating sea haze and other obscurants giving the system the ability to read the letters on the side of vessels. The MQ-9B also has an electro-optical sensor for streaming video imagery that can distinguish a man sized target at seven miles distance. The modification of the MQ-9 system attaches a belly-mounted Raytheon AN/APS-134 SeaVue^{TM} XMR multi-mode maritime search radar. This modification aids in the classification of moving ships at a distance of fifty miles away. It is equipped with AIS and will interrogate cooperative surface ships to assist in classification of threats (Global Security.Org 2011).

General Atomic MQ-9 Guardian Characteristics	
Primary Function	Unmanned Air Surveillance - Maritime
Contractor	General Atomics Aeronautical Systems, Inc.
Power Plant	Honeywell TPE331-10GD turboprop engine
Thrust	900 shaft horsepower maximum
Wingspan	66 feet (20.1 meters)
Length	36 feet (11 meters)
Height	12.5 feet (3.8 meters)
Weight	4,900 pounds (2,223 kilograms) empty
Maximum takeoff weight	10,500 pounds (4,760 kilograms)
Fuel Capacity	4,000 pounds (602 gallons)
Payload Capacity	3,750 pounds (1,701 kilograms)
Speed	Cruise speed around 230 miles per hour (200 knots)
Range	1,150 miles (1,000 nautical miles)
Ceiling	Up to 50,000 feet (15,240 meters)
Crew (remote)	Two (pilot and sensor operator)
Unit Cost	$53.5 million (includes four aircraft with sensors) (fiscal 2006 dollars)
Initial operating capability	October 2007
ISR Payload	MTS-B, SAR, SeaVue XMR, EO/IR, AIS, ARC-210, RT-5000, INMARSAT

Table 13. "MQ-9 Guardian Specifications." (Global Security.Org 2011)

4. Payload Systems

a. EL/ M-2022U Maritime Surveillance Radar System

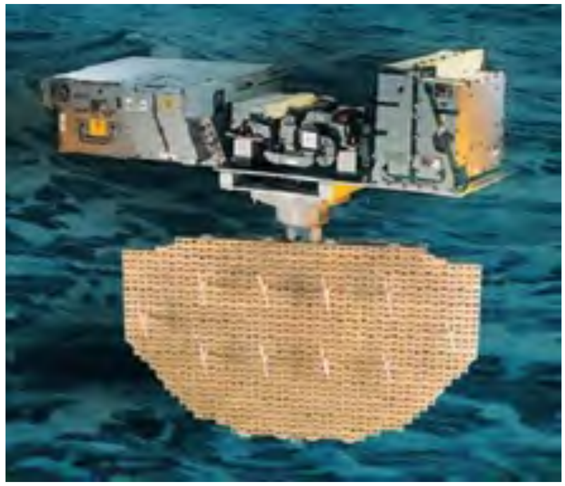

Figure 31. “Maritime Surveillance Radar System.”

The EL/M-2022U, (Figure 31 and Table 14) is multi-role, multi-mode, airborne maritime surveillance radar. It employs a Synthetic Aperture Radar and inverse synthetic aperture Radar (ISAR) for use with the Heron TP UAS. ISAR is ideally suited or the imaging of moving targets in high seas. The system has automatic tracking of moving targets at any speed. It is capable of operation day or night and in all weather conditions. It is also capable of penetrating clouds, rain, smoke and fog (Jane's Electronic Mission Aircraft 2011).

EL/M-2022 Maritime Patrol Radar Specifications	
Detection range	up to 230 miles (EL/M-2022A)
Track-while-scan	up to 256 targets (EL/M-2055A, including IFF tracking)
Operating Temperature	-4 to +131F (EL/M-2022A)
Altitude	sea level to 30,000 ft (EL/M-2022A)
Power	115 V AC (EL/M-2022A, 3-phase, 400 Hz, 2 kVA (maximum), MIL-STD-704 compliant)
Power consumption	1,000 W (EL/M-2022U, vertical take-off/landing UAV); 2,000 W (EL/M-2022H); 2,300 W (EL/M-2022U, medium-altitude long-endurance UAV)
Weight	110 lbs. (EL/M-2022U, vertical take-off/landing UAV); 165 lbs. (EL/M-2022H); 251 lbs. (EL/M-2022U, medium-altitude long-endurance UAV); 198-220 lbs. (EL/M-2022A, approximate, configuration dependent, excluding operator's console)

Table 14. EL/M 2022 Maritime Patrol Radar

Northrop-Grumman had its first flight test in February, 2010. For tracking, the system uses the Defense Advanced Research Projects Agency's (DARPA) NetTrack tool. NetTrack is designed for reconnaissance, surveillance and tracking of ground targets and is able to detect people, animals, water craft and land vehicles. The VADER system is comprised of a receiver/exciter/processor unit mounted in the vehicle fuselage and an external pod mounted antenna unit. The versatile radar system can track at varying ranges. Although it is designed for a medium altitude aircraft, it can track at varying altitudes and airspeeds. (Northrop-Grumman 2011)

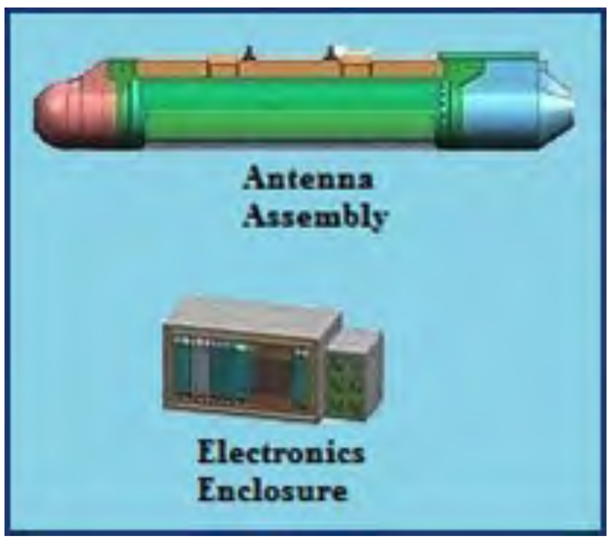

Figure 32. "Vehicle and Dismount Exploitation Radar (VADER)."

b. Wescam MX-Series

Wescam, Figure 34 and Table 15, produced by L-3 Technologies, comes in 3 sizes in their MX series EO/ IR gimbaled imaging systems (MX-10, MX-15 and MX-20). The MX-20 is the largest of the MX series and can be configured with up to 6 sensors. The unit has 24/7 EO imaging and has enhanced night imaging with laser illumination. The systems AVGT unit can combine video with geo-tracking, providing excellent target tracking. The imaging resolution is 1080p and has 2 mega-pixel EO Zoom and spotter cameras (Communications, L3 2011).

MX -20 Specifications			
High magnification thermal imager (standard)		**Gimbal and turret**	
Detector:	Gen 3 InSb staring array	**Active gyro-stabilization:**	5-axis (3 inner, 2 outer)
Spectral range:	3 to 5 µm	**Vibration stabilization:**	6-axis passive isolation
Resolution:	640 × 512	**LoS jitter:**	<4 µrad RMS
Fields-of-view (h):	18.2° to 0.24° in four stages (720p and 1,080p)	**Slew rate:**	0-1 rad/s
Color daylight TV with zoom lens (standard)		**Azimuth range:**	360° continuous
Type:	Color HD	**Elevation range:**	-120 to +90°
Resolution:	2 megapixels	**Power:**	320 W (average); 1,000 W (max)
Fields-of-view (option A):	41.3° to 2.2° (7200p); 44° to 3.2° (1,080p)	**Dimensions:**	
Fields-of-view (option B):	21.3° to 1.83° (7200p); 18.2° to 2.75° (1,080p)	**Diameter:**	530 mm
TV with step-spotter lens (optional)		**Height:**	670 mm
Type:	Color HD or Monochrome HD	**Weight:**	84.1 kg
Resolution:	2 megapixels		
Fields-of-view:	0.115° to 0.61° (720p); 0.17° to 0.92° (1,080p) in 4-steps	**Laser illuminator (optional)**	

MX -20 Specifications			
MX-Day/Night Spotter{TM} with dual-channel step-spotter (requires Color HD camera above)		**Type:**	Diode (ANSI Class 4)
Type:	Charge-multiplying CCD (mono-chrome)	**Wavelength:**	860 nm
Wavelength:	450 1 1,000 nm (selectable)	**Mode:**	Continuous, pulsed
Fields-of-view (h):	0.14° to 0.73° in 4-steps (720p and 1,080p)	**Beam diver-gence:**	Wide, narrow or ultra-narrow. (Matched to MX-Night Spotter).
Eye-safe laser rangefinder (optional)			
Type:	Er: glass (ANSI Class 1)		
Wavelength:	1.54 µm		
Pulse rate:	12 ppm		
Range (typical):	30 km (50 km range gate)		
Range resolution:	±5 m		

Table 15. “MX 20 Specifications.” (Jane's Intelligence 2011)

c. *Multi-Spectral Tracking System (MTS-B)*

The AN/ASS-52 Multi-Spectral Tracking System (MTS-B), Figure 33 and Table 15, (Jane's Intelligence 2011) is a high altitude adapted MTS-A system and was specifically developed for use in the MQ-9 Reaper. The system uses various sensor options including EO TV, image intensified TV, a laser illuminator, a laser range finder, a spot tracker, image fusion and other avionics. By combining these various sensors, it would generate an enhanced image and employ automatic image optimization techniques.

Figure 33. “Multi-Spectral Tracking System.”

AN/ASS-52 MTS-B Specifications	
Fields-of-view:	
Ultra-narrow IR:	0.23 0.31
Ultra-narrow TV:	0.08 0.11
Narrow IR/TV:	0.47 0.63
Medium-narrow:	2.8 3.7
Medium:	5.7 7.6
Medium-wide:	17 22
Wide:	34 45
Electronic zoom:	2:1 and 4:1 (IR/TV in smallest FoVs)
Gimbal angular coverage	
Azimuth:	360 continuous
Elevation:	-135 to +40
Slew rate:	2 radians/s
Max Indicated Air Speed:	> 200 kt (370 km/hr; 230 mph)
Automatic video tracking:	Centroid, area and feature
Video outputs:	Digital, RS-170 (525-line) and others
Interfaces:	MIL-STD-1553 data bus and/or discrete controls
Power:	28 V DC
Cooling:	Self-contained
Environmental:	MIL-E0-5400 and MIL-STD-810
Dimensions	
WRA-1 (turret) - diameter:	22 in
WRA-2 (electronics unit)	
Length:	14.4 in
Width:	4.9 in
Height:	7.6 in
Weights	
WRA-1 (turret):	230 lb.
WRA-2 (electronics unit):	25 lb.

Table 16. “AN/ASS-56 MTS-B Sensor Specifications.”

Figure 34. “Raytheon SeaVueTM.” The Raytheon SeaVue^{TM} system is a lightweight modular X-band surveillance Radar package for a maritime environment.

SeaVue^{TM} incorporates a number of radar modes including Doppler beam sharpening, SAR/ISAR, Search 1 and Search 2. In Search 1 mode, the system is used to detect small targets in high sea states. In Search 2 mode, the system is used for extended range detection when there are multiple potential targets. The system can emulate a parabolic reflector, as well as a planar array, depending on the needed modes (Jane's Intelligence 2011).

Generic SeaVue{TM} Specifications	
Dimensions	
Transmitter Height	279 mm (10.98 in)
Width	330 mm (12.99 in)
Depth	498 mm (19.61 in)
RESP: Height	257 mm (10.12 in)
Width	391 mm (15.39 in)
Depth	498 mm (19.61 mm)
Weights	
Typical antenna	23 kg
Transmitter	30 kg
RESP	37 kg
Performance	
Frequency	9.4-9.8 GHz
Power output	8, 15 or 50 kW (peak)
Detection range: Individual life raft	67 n miles (124 km, 77 miles)
Patrol boat	119 n miles (220 km, 137 miles)

Table 17. “Generic SeaVue^{TM} Specifications.

IV. CONCEPT DEFINITION

A. MODELING AND SIMULATION

1. Modeling and Simulation Overview

Modeling and simulation allows for the examination of system performance requirements to aid in determining the overall system MOPs and gauging system development. During needs and requirements decomposition, there were some unknowns crucial to the concept of operations development, which needed exploration to ensure proper requirements definition in support of system objectives. For the purpose of this project, a simulation model was created in Microsoft Excel to evaluate the tradeoff of system requirements such as number of UASs, speed of UASs, UAS endurance time. Also included are systems constraints and assumptions such as frequency of mother ship attacks on commercial vessels, speed of pirate vessels, and the minimum threshold time that allows successful evasive action by a commercial vessel. The objective of the system is to successfully detect, locate, classify and identify enemy mother ships with enough time to warn commercial vessels so they can avoid attack. The model allows the adjustment of each parameter to determine the impact to the system's successful detection capability and MOE for various possible configurations.

Some of the inputs into the model included constants such as the probability of the detection system to detect various size targets. Data was acquired through market analysis and interviews. Other factors in the model were second order, based on modeling to meet objectives set forth in the MOEs.

There was a need to determine the right size corridor to continue to facilitate easy and economical transport of supplies through the affected zone yet enable a support system to be successful. Because of the large number of variables between the possible components of the system, the modeling effort was needed to answer the proper scanning size for each system configuration. MOPs for radar scanning parameters were developed using this Microsoft Excel modeling tool.

2. Number of UASs Required to Cover Area of Interest

The differences of performance (speed of UAS, number of UASs allotted, speed of target vessels, operational altitude, time on site, etc.) between each potential ISR platform made it necessary to create a model for evaluation in order to determine the most capable asset to complete the mission. All parameters discovered during the product research effort were used as inputs into the model to determine the number of a specific platform UASs to yield the appropriate level of system success. Using the model results, the above quantitative factors were used to determine the final system measures of performance (MOP) to best meet the customer needs.

B. PAIRWISE ANALYSIS AND QFD

A survey was sent out to the stakeholders and the results were run through a pair-wise comparison tool. Operational requirement weights were established to support QFD analysis. As can be seen in Figure 35, “Customer Requirements versus MOEs,” detection was the most important function to the stakeholders. Operators described detection as a major capability gap in their descriptive responses to the survey and mentioned the need for maritime surface radar assets. Figure 35 presents “Customer Requirements versus MOEs, and Figure 36, the results of the pair-wise comparison.

Design Characteristics (Hows)

Customer Requirement (Whats)			A: MOE Identity C2 Designated Contacts	B: MOE: Persistently Track Contacts	C: MOE: Determine Classification	D: MOE Mission Data Relay	E: MOE BLOS Communications	F: MOE Detection of Pirate Mother Ships	G: MOE Locate Pirate Mother Ship	H: MOE Broad Area Surveillance	
Detection	0.3358	0.3358						9		9	
Relay Communications	0.1835	0.1835				3	9				
Continuously Track Contacts	0.1119	0.1119		9					6	9	
Persistent/Endurance	0.0959	0.0959		9						9	
Interoperability	0.0839	0.0839				9	6				
Locate Contacts	0.1441	0.1441		6		9		3	9	3	
Provide Imagery	0.0448	0.0448	9		9						
Check Sum	1.0000	1.00									
[redacted]											
Weighted Performance			0.4	2.7	0.4	2.6	2.2	3.5	2.0	5.3	19.0
Percent Performance			0.021	0.144	0.021	0.137	0.113	0.181	0.103	0.280	1.000
											Check

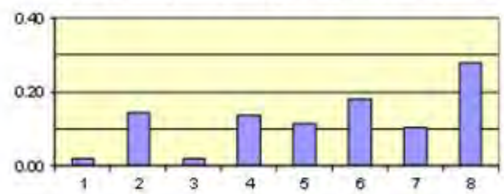

Figure 35. "Customer Requirements versus MOEs."

Criteria	Criteria	Detection 1	Relay Communications 2	Continuously Track Contacts 3	Persistent/Endurance 4	Interoperability (BLOS C2) 5	Locate Contacts 6	Provide Imagery 7	Weights
Detection	1	1	1.83	3	3.5	4	2.33	7.5	0.3358
Relay Communications	2	0.5464	1	1.6393	1.9126	2.1858	1.2732	4.0984	0.1835
Continuously Track Contacts	3	0.3333	0.61	1	1.1667	1.3333	0.7767	2.5	0.1119
Persistent/Endurance	4	0.2857	0.5229	0.8571	1	1.1429	0.6657	2.1429	0.0959
Interoperability(BLOS C2)	5	0.25	0.4575	0.75	0.875	1	0.5825	1.875	0.0839
Locate Contacts	6	0.4292	0.7854	1.2876	1.5021	1.7167	1	3.2189	0.1441
Provide Imagery	7	0.1333	0.244	0.4	0.4667	0.5333	0.3107	1	0.0448
		0.3	0.2	0.1	0.1	0.1	0.1	0.0	1.0000
									Check

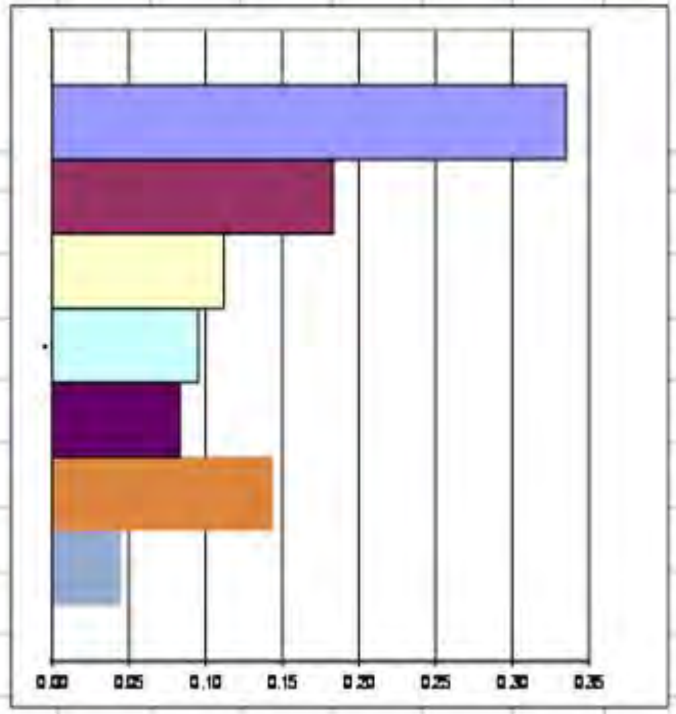

Figure 36. “Pair-Wise Comparison Results.”

Operational functions or activities were translated into operational measures of effectiveness (MOE) in the second level of the QFD. MOEs were evaluated for relative importance and assigned numbers on a scale of low (3), medium (6), and high (9) (Figure 35). After the assignment of proper scale to MOEs, a third level of mapping was performed to show the derivation of MOP shown in Figure 37, “QFD 2. Design Characteristics Relative to Functions.”

Functions (Hows)

Design Characteristics (Whats)	Weights		MOP: Range to detect RCS 25 SqM at minimum of 20K ft ALA	MOP: LOS Capability Range	MOP: Number of surface tracks while in sensor view	MOP: Hours on station @ Mission Radius	MOP: BLOS Capability Range	Surface Vessel detection RCS SqM Accuracy @ 20K FT	MOP Produce Visible & IR NIIRS Level 7 at 20K FT AGL w/ideal Weather Conditions	MOP: Speed
			Mi,M^2, @Ft MSL,	1.0	Units	Hrs @ Mi	Units	Units	Units	Units
A: MOE Identify C2 Designated Contacts	0.021	0.021							9	6
B: MOE: Persistently Track Contacts	0.144	0.144	6		9	3		9		6
C: MOE: Determine Classification	0.021	0.021							9	6
D: MOE Mission Data Relay	0.137	0.137		9			9			
E: MOE BLOS Communications	0.113	0.113					9			
F: MOE Detection of Pirate Mother Ships	0.181	0.181	9					3		9
G: MOE Locate Pirate Mother Ship	0.103	0.103	9					9		9
H: MOE Broad Area Capability	0.280	0.280				9	6			
Check Sum	1.000	1.00								
Goal Value										
Threshold Value										
Weighted Performance			3.4	1.2	1.3	2.9	3.9	2.8	0.4	3.7
Percent Performance			0.174	0.063	0.066	0.150	0.200	0.141	0.019	0.187

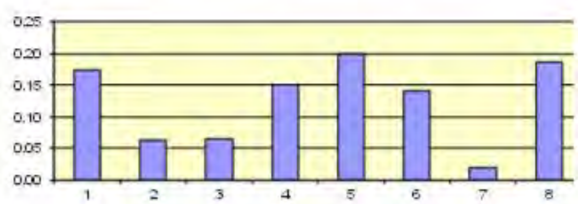

Figure 37. “QFD 2. Design Characteristics Relative to Functions.” A third level of the QFD, development and alignment of MOP.

In addition to the formal analysis there were two Interim Project Reviews (IPRs) during our project execution. Stakeholder feedback from each review was incorporated into all affected analyses and deliverables. A brief sampling of representative feedback includes:

IPR1

- Establish queue for ISR assets
- Define classification for "threat"
- Establish AIS capability
- Determine tracking capability/reestablish target if signal is lost
- Understand data fusion technology amongst different assets

IPR2

- Clarify/define what is meant by "continuously tracking contacts"
- Define whether C2 is within the scope of PMSW&RS
- Reduce scope to evaluate time to detect, confirm, a pirate
- Establish the use of Airborne Communications Relay.

The complete list of comments from each of the IPRs can be seen in Appendix C, "Stakeholder Refinement."

C. CANDIDATE SYSTEM

The Heron TP, Guardian and the LEMV systems are analyzed.

1. Simulation of Specific UASs

UAV	*Cruising Speed*	*Flight Endurance*	*Cruising Altitude*
Heron	113 Knots	36 hours	20,000 ft
LEMV:	80 knots	504 hours (21 days)	20,000 ft
Guardian:	150 knots	25 hours	25,000 ft
Scan Eagle:	60 knots	27 hours	20,000 ft
Fire Scout:	110 knots	8 hours	20,000 ft

Table 18. "UAS Characteristics to be used in Model."

Once the general parameters of interest have been determined (warning distance, radar ranges, pirate speeds, and protection zone size), the model was used to evaluate different types of UAS platforms. Each UAS has unique characteristics such as speed, altitude and detection aperture (area of instantaneous scan). These parameters were loaded into the model and the simulation was run to assess the performance in each operational situation. The output of the model was used to determine the number of UASs required for each platform to achieve the threshold and objective MOEs with a high successful detection rate.

2. Input Parameters into the Model for each System Configuration

MA UAV	MA Speed (knots)	MA Endurance (hours)	MA Altitude (feet)	MA Radar Range (nm)	Pirate Speed (knots)	Zone Size (nm)	Warning Distance (nm)
Heron	190	24	20,000	160	17	800x800	103
LEMV	80	504	20,000	60	17	800x800	103
Guardian	150	25	25,000	75	17	800x800	103

Table 19. "Model Inputs for Medium Altitude UASs."

3. Outputs of the Model

The number of UASs needed to meet the threshold and objective for each UAS configuration was generated from the simulation model. The model does not take into account UAS downtime due to unexpected repairs and maintenance. To accommodate for real world operations, an additional UAS will be required to compensate for these downtimes and meet the full operation time on station.

	UAV	Model Type	# of UAVs needed to meet threshold (80%)	# of UAVs needed to meet objective (90%)
Med Alt UAVs	Heron	Med Alt UAV's only	UAV's: 3 (96%)	UAVs: 3 (96%)
	LEMV	Med Alt UAV's only	UAV's: 5 (85%)	UAV's: 6 (97%)
	Guardian	Med Alt UAV's only	UAV's: 5 (98%)	UAV's: 5 (98%)

Table 20. "Model Outputs for Medium Altitude UASs."

4. Recommendations

The medium altitude concept was able to outperform the alternate concept (high and low attitude UASs) while using fewer total UASs and it can be completely operated and maintained from a land based launch site requiring less specialized equipment, manpower, and Navy assets. The platform allocations are to be used for cost analysis and final selection.

	UAV	Model Type	# of UAVs needed to meet threshold (80%)	# of UAVs needed to meet objective (90%)
Med Alt UAVs	Heron	Med Alt UAV's only	UAV's: 2 (96%)	UAVs: 2 (96%)
	LEMV	Med Alt UAV's only	UAV's: 4 (85%)	UAV's: 5 (97%)
	Guardian	Med Alt UAV's only	UAV's: 4 (98%)	UAV's: 4 (98%)

Table 21. "UAS Selections and Performance to be used with Cost Analysis."

IV. ANALYSIS OF ALTERNATIVES

A. SYSTEMS ENGINEERING ANALYSIS: EFFECTIVNESS AND PERFORMANCE ASSESSMENT WITH MATRIX BASED DECISION ANALYSIS

In the mathematical model, the alternative with the highest sum of product score value is the best among the different alternatives. Each one of the alternatives is assigned a weight value by the stakeholder and prioritization scheme, and this value is then applied in model calculations to arrive at a final weight value.

Decision Matrix				
Evaluation Measure	**Attribute Weights**	Alternatives		
		Heron	LEMV	Guardian
MOP: Range to detect RCS 25 SqM at minimum of 20K ft MSL	0.1743	**0.73**	**1.00**	**0.00**
MOP: LOS Capability Range	0.0626	**1.00**	**1.00**	**1.00**
MOP: Number of surface tracks while in sensor view	0.0658	**1.00**	**1.00**	**0.80**
MOP: Hours on station @ Mission Radius	0.1500	**0.33**	**1.00**	**0.25**
MOP: BLOS Capablility Range	0.1998	**1.00**	**1.00**	**1.00**
Surface Vessel detection RCS SqM Accuracy @ 20K FT	0.1408	**0.67**	**0.90**	**1.00**
MOP Produce Visible & IR NIIRS Level 7 at 20K FT AGL w/Ideal Weather Conditions	0.0194	**0.50**	**0.50**	**0.50**
MOP: Speed	0.1872	**0.92**	**0.00**	**1.00**
Total Score		**0.78**	**0.79**	**0.69**

Table 22. "Alternatives Selection Decision Matrix."

Table 22 illustrates a snapshot of alternative selection decision matrix. This matrix is used as a tool to mathematically calculate and rank each MOP. Each alternative column contains score values calculated based on each alternative raw score scaled to its threshold and objective values.

B. SCORE NORMALIZATION

A question during the analysis was how to derive these scores, and how can they be used to compare to each other if the threshold and objective values of each of measure of performance are can be expressed in different units and quantities. This question is resolved by performing a "normalization" operation on the threshold and objective values. "Normalization" is a mathematical operation process where a maximum value of "1" is assigned to the "objective value," and a minimum value of "0" is assigned to the "threshold" value; then the objective score value for each measure of performance is "scaled" into the max-min scale of 1 to 0. Using this scaling operation, all alternative scores can be combined and compared on an equal and leveled baseline. For example, for the Detection Range MOP, the threshold value is 80 eighty miles, and the objective value is 200 miles, an alternative with a specification of 150 miles can be "normalized" to a value of 0.583:

$$\frac{150 - 80}{200 - 80} = 0.583$$

By using the normalization process, a raw specification value can be converted to a unit-less value that is used for comparison between different alternatives, all of which have different units and quantities of measurement.

C. WEIGHT SENSITIVITY ANALYSIS

There are a total of eight MOPs defined for this project. Each MOP has a weighting factor associated with it. Changing the weighting factor can change the alternative total score. Figure 38, "Sensitivity Analysis (Detection Range)" shows an example of the weighting factor sensitivity plots for detection range. The lines indicate the change in the rankings of the various alternatives throughout the variation in the attribute weights. The values of attribute weights only make sense in the 0 – 1 range. Investigating the ranking of the alternatives at an attribute weight of 0 indicates that the Guardian would be the highest ranked solution with respect to Detection Range. If the attribute weighting were changed to 1, then the Heron and the LEMV would be tied for the highest ranking, with the Guardian as the lowest ranked solution alternative. Each MOP was evaluated. The remainder of the charts and analysis can be found in the Appendix B: "Sensitivity Analysis."

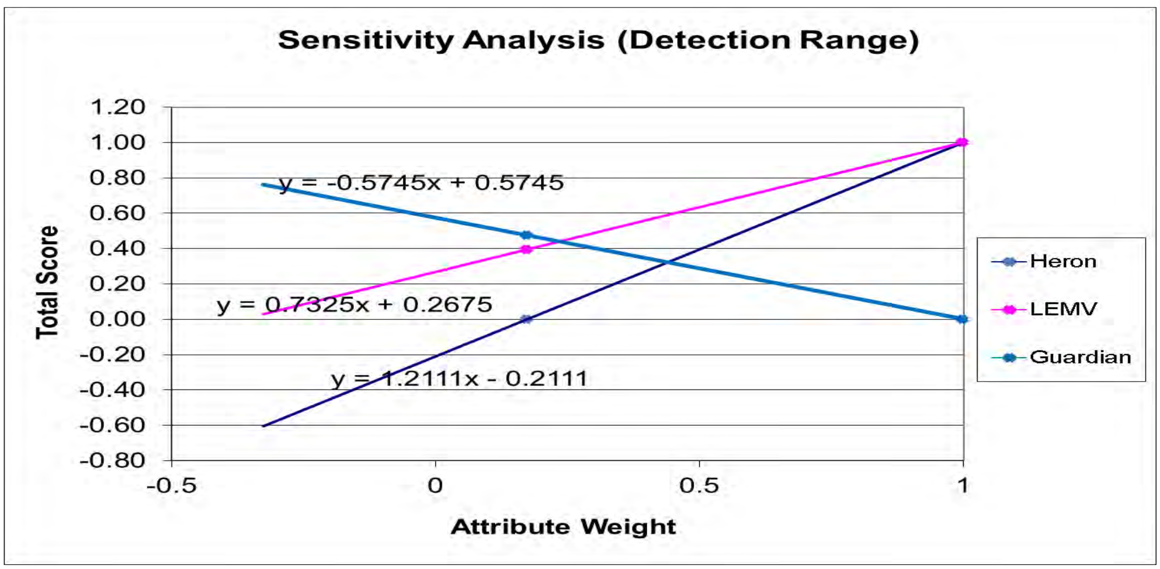

Figure 38. "Sensitivity Analysis (Detection Range)"

D. COST AS AN INDEPENDENT VARIABLE (CAIV)

1. Scaled Cost

The dollar figure in the CAIV analysis is a cost per flight hour metric (CPFH). The CPFH operational metric is a compilation of operational manpower, fuel, maintenance, maintenance manpower, ground control expenses, consumables, and repairable items. These operational elements contribute most significantly to costs that are directly related to aircraft flight time. The hour portion of the CPFH metric is calculated based mission duration, which is also the basis of the analysis in determining the number of assets needed to complete the mission. The dollar (cost) portion is based on the following assumptions and cost analysis techniques supported by Naval Air Systems Command (NAVAIR) 4.2 Cost Department (Naval Air Systems Command, AIR 4.2.2 2010):

- The higher the operational ceiling, the larger the search radius of the radar
- The faster the operational speed, the more area the particular radar can cover
- The longer the endurance, the more area the UAS can cover (dependent upon speed)
- In situations where CPFH could not be found comparable platforms were analyzed and adjustments were made to arrive at a CPFH dollar value. Adjustments were consistent with NAVAIR 4.2 methodology
- Endurance is NOT time on station.
- Heron’s CPFH estimate leveraged off of the BAMS estimate generated by NAVAIR 4.2 as they have similar capability, and complexity adjustments were made.
- Guardian’s CPFH is derived from MQ-9 Reaper’s CPFH as they are very similar platforms. This was pulled directly from the Air Force Total Ownership Cost (AFTOC) data base that is updated quarterly. Minor adjustments were made for capability.
- If a range of data was given the mean was taken for each category
- NAVAIR 4.2 subject matter experts (SMEs) helped with adjustments and complexity factors.

- LEMV cost data is very immature and adjustments were made based on smaller airships and preliminary NAVAIR 4.2 estimates. The adjustments took into account:
    - Increased payload capability
    - Increased loiter time
    - Number of engines
    - Fuel consumption
    - Operational/Maintenance/Ground control manpower
    - Size and complexity of the LEMV asset
- All cost figures are in FY 12 dollars.

Based on discussions with operations research analysts within the Army's Cost division for UASs, the Army has not established a CPFH metric for LEMV; thus other avenues of cost estimation were pursued. Data bases that are currently used to collect operational expenditures of Army assets are The Operating and Support Management Information System (OSMIS) and Army Visibility and Management of Operating and Support Costs (VAMOSC). These data bases log operational information on consumables and repairable items, mean time between failure, fuel consumption, and maintenance man hour information amongst other operational categories. Additionally, NAVAIR 4.2 Cost Department developed a preliminary operational cost estimate on LEMV when it was proposed to the Navy. Leveraging the early estimate, and information from the Army data bases, an operational cost estimate was generated and then normalized into a CPFH metric. There were instances in which LEMV specific data was non-existent; thus data on a comparable airship was used to generate portions of the estimate. Fuel consumption is based on the engine type, number of engines and LEMV mission duration which is normalized into a CPFH. The final piece of the CPFH metric is operational manpower (pilots). For both the fuel and operational manpower, the estimate was adjusted for inflation.

Tables 23 and 24 show the results of the cost analysis and the assumptions applied. On a dollar per flight-hour basis only, LEMV is the clear solution; however, the asset's capabilities must be taken into consideration. The maximum mission time is assumed to be twenty-four hours a day for seven consecutive days. This is how the 168 hour mission time is generated. To generate the scaled cost calculation, "Dollar per Flight Hour" is multiplied by quantity of

“UASs to Complete Mission” (threshold/objective) which is then multiplied by the “Mission Duration”. To scale the cost, the “Total Cost” number was divided by one million. The calculations account for down time due to fueling, standard maintenance, and time to get to and from area of interest. Table 23 illustrates the figures described in the CAIV analysis. Flowing from left to right the cost per flight hour is multiplied by the “# of UASs to Complete Mission” by the duration to get the mission cost. (scaled cost = mission cost / 1 million).

Table 24 illustrates the figures used to calculate the OMOE values as described in OMOE Analysis. Moving from top to bottom the attribute capability weights are multiplied by the decision matrix data to get weighted values. The weighted values are then summed left to right to generate the OMOE values.

	# UAV to Complete Mission (Threshold)	# UAV to Complete Mission (Objective)	Mission Duration (Hrs)	Total Cost (Threshold)	Total Cost (Objective)	Scaled Cost (Threshold) FY12 $M	Scaled Cost (Objective) FY12 $M	Decision Matrix Total Score
Heron	2	2	168	$ 2,251,200	$ 2,251,200	2.251	2.251	0.780
LEMV	4	5	168	$ 1,411,200	$ 1,764,000	1.411	1.764	0.789
Guardian	4	4	168	$ 3,158,400	$ 3,158,400	3.158	3.158	0.690

Table 23. "CAIV Analysis."

	Detection Range	Line of Sight	Track Capacity	Hours on Station	Beyond Line of Sight	Detection Accuracty Range	NIIRS	Speed	Decision Matrix Total Score
Attributed Capability Weights From Decision Matrix									
	0.174	0.063	0.066	0.150	0.200	0.141	0.019	0.187	1.000
Decision Matrix Data									
Heron	0.73	1.00	1.00	0.33	1.00	0.67	0.50	0.92	
LEMV	1.00	1.00	1.00	1.00	1.00	0.90	0.50	0.00	
Guardian	0.00	1.00	0.80	0.25	1.00	1.00	0.50	1.00	
Attributed Capability Weights Multiplied by Decision Matrix Data (weighted value)									
Heron	0.13	0.06	0.07	0.05	0.20	0.09	0.01	0.17	**0.780**
LEMV	0.17	0.06	0.07	0.15	0.20	0.13	0.01	0.00	**0.789**
Guardian	0.00	0.06	0.05	0.04	0.20	0.14	0.01	0.19	**0.690**

Table 24. "UAS OMOE."

2. Overall Measure of Effectiveness (OMOE) Analysis

Detailed OMOE analysis in the areas of Detection Range, Line of Sight, Track Capacity, Hours on Station, Beyond Line of Sight, Detection Accuracy Range, and NIIRS (sensitivity analysis) was performed in order to determine which UAS asset performed the best independently of cost. The calculation applied "attribute capability weights" from the decision matrix in the aforementioned categories, as well as calculated "decision matrix data." The "attributed capability weights" were multiplied by the "decision matrix data" in each category for each of the three UAS alternatives to generate a weighted capability value. These values were then summed together to determine the OMOE data points ultimately determining the most capable UAS. Note the "1" values in the OMOE table indicate that the objective value was met relative to the MOPs.

Based on the OMOE analysis in Table 24, it is clear that independent of cost, LEMV has outperformed the Heron TP and Guardian. LEMV exceeds the other two considerations in hours on station and provides the greatest overall probability of successfully completing the mission at the objective and threshold levels. However, in order for LEMV to meet the objective, an additional asset was needed. With the resulting weights generated from the OMOE analysis, combined with the objective and threshold analysis, the team was able to generate a basis for the CAIV analysis.

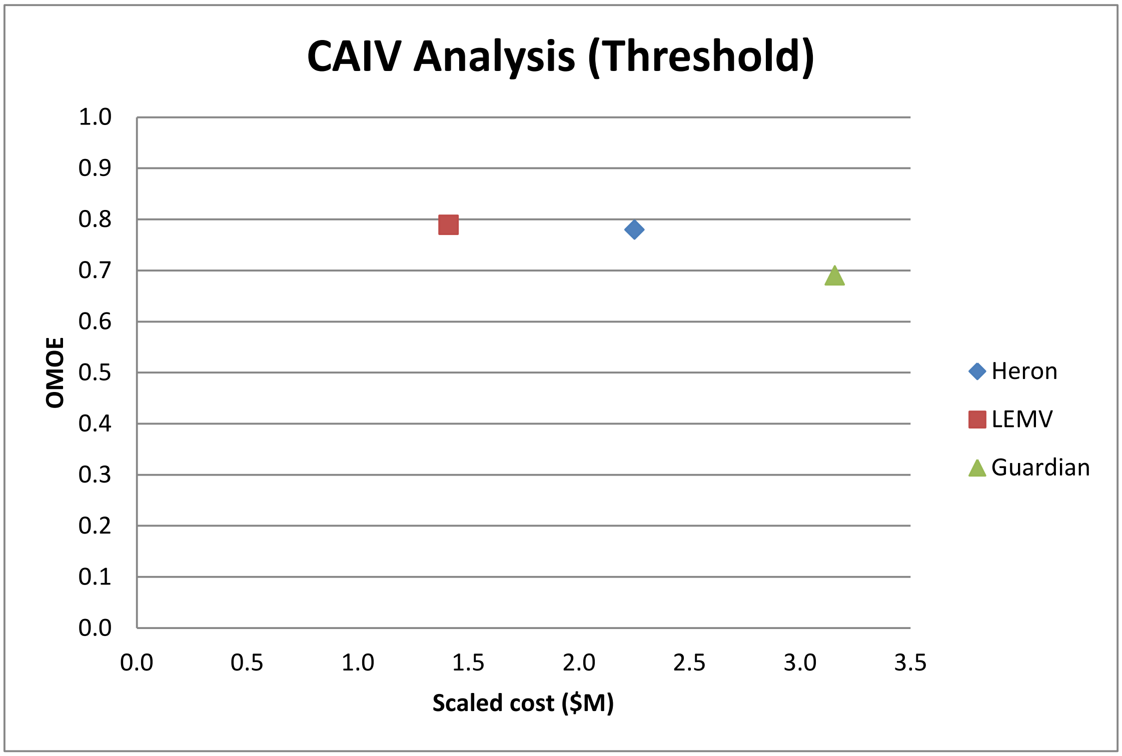

Figure 39. “CAIV Analysis Threshold Chart.”

The three assets meet or exceed the threshold of 80 % (< 90%) confidence that they will detect a threat in the area of interest, utilizing the quantity of assets in the Threshold/Objective analysis. LEMVs ETOS had to be normalized in order to make an effective comparison to Heron TP and Guardian as it far exceeded the other two candidates. In addition, the LEMV is the least expensive on a cost per flight-hour basis which makes it a very desirable option that has the ability to complete the mission at hand at or slightly above the 80% threshold. This ultimately does not change the outcome. The LEMV asset not only ranks the highest in capability but is also the lowest in cost. Heron TP ranks very close to LEMV, however; it is more expensive for slightly less capability. Guardian is the most expensive due to its high CPFH and also provides the least capability. This analysis allows the user to make an informed decision on desired capability compared to the amount of money spent to complete the mission.

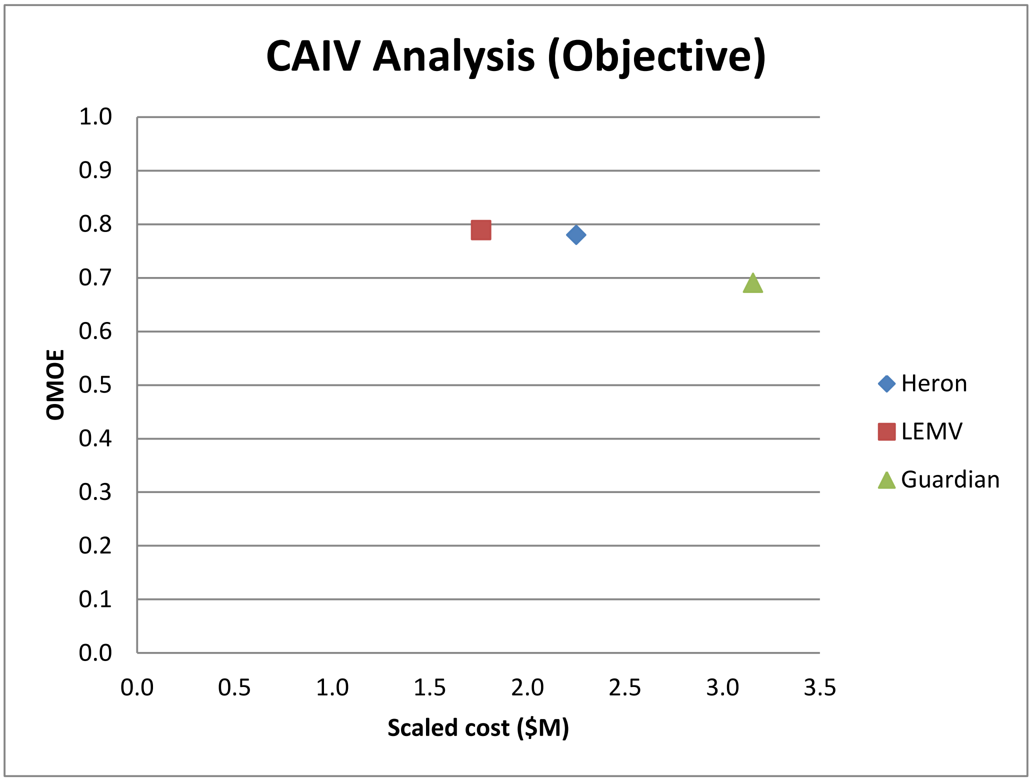

Figure 40. “CAIV Analysis Objective Chart.”

V. CONCLUSIONS AND RECOMMENDATIONS

1. Risks

The PMSW&RS project risks are summarized in the following section, and represented in Figure 41, "PMSW&RS Project Risks."

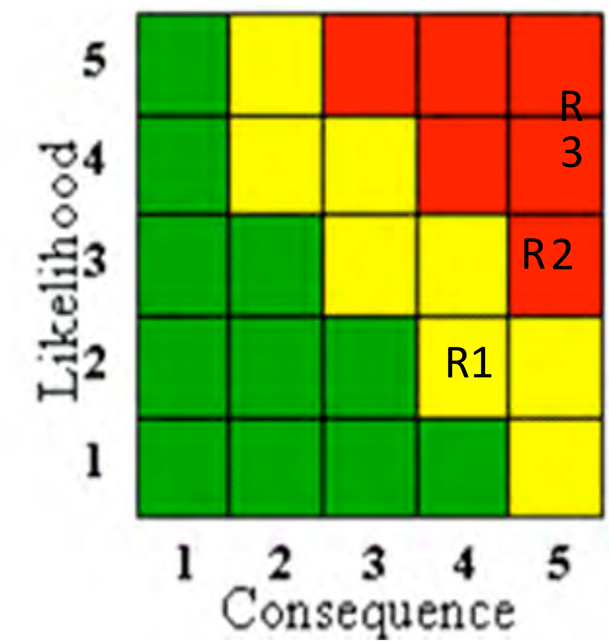

Figure 41. "PMSW&RS Project Risks." This risk matrix shows the current risks associated with the PMSW&RS program.

a. Risk 1: UAS may not be granted access to use forward operating base (L2, C3)

- Description of risk: UAS forward operating base is not identified for UAS launch and recovery operations,
- Statement of cause: The identified airfields are not on U.S. Soil and would require local basing agreements. No conclusive evidence was discovered to assure the team that host nations would grant basing rights for the UAE and Maldives FOBs.
- Consequence if risk is realized: Mission radius will significantly increase and reduce effective time on station.

b. Risk 2: Unsuccessful use of detection queuing filters (L3, C5)

- Description of risk: UAS detection queuing filters and algorithms may be unsuccessful.

- Statement of cause: Very little is known at this time about the success rate of these software systems. Given the quantity of ships in the HOA AOR, it could prove to be a major technical and cost risk for success.

- Consequence if risk is realized: UAS Operator workload would increase and productivity would decrease, thereby decreasing the time needed to detect Pirate Mother Ships and then safely warning commercial vessels of their position, thus decreasing the probability of successful avoidance.

c. Risk 3: Commercial vessels not utilitzing the automatic identification system (AIS) (L4, C4)

- Description of risk: Civilian captains choose not to utilize AIS.

- Statement of cause: In the HOA AOR currently, civilian captains have been turning off their AIS transponder because the sensor was being used as a tracking device by Pirate Mother Ships to find commercial vessels.

- Consequence if risk is realized: UAS may have difficulty discerning Pirate Motherships from commercial ships. May significantly increase UAS operator workload.

2. Conclusions and Recommendations

The PMSW&RS project tried to tackle a very complicated and multi-faceted real world problem in the naval maritime surface domain. The recommended system of choice represents the result of several logical and methodical system engineering analysis exercises that differentiates all relevant alternatives allowing the selecting of the best alternative.

The optimal UAS selection for the PMSW&RS mission utilizes the LEMV to achieve acceptable performance at the least cost. LEMV dominated the other candidates by achieving the lowest CAIV value of 1.41 and 1.76 at 80% and 90% confidence interval respectively. The Heron TP has a lower CAIV value than Guardian at 2.25 for both 80% and 90% detection probabilities. The Guardian UAS CAIV value was the highest of all three assets at 3.15 for both 80% and 90% detection probability respectively. If the evaluation is based on performance only, ignoring cost, the LEMV UAS provides the best option to the stakeholders. (Note: The LEMV requires an additional asset to meet the objective. This has already been accounted for in the CAIV and OMOE analysis. If cost is the most significant consideration, the LEMV would provide the best option as well.

The LEMV UAS is the recommended asset for monitoring and early warning of piracy activities in the HOA AOR. The LEMV achieves both the performance threshold of 80% and objective of 90% at the lowest cost. Second to LEMV would be Heron TP UAS followed by Guardian UAS.

	# UAV to Complete Mission (Threshold)	# UAV to Complete Mission (Objective)	Mission Duration (Hrs)	Total Cost (Threshold)	Total Cost (Objective)	Scaled Cost (Threshold) FY12 $M	Scaled Cost (Objective) FY12 $M	Decision Matrix Total Score
Heron	2	2	168	$ 2,251,200	$ 2,251,200	2.251	2.251	0.780
LEMV	4	5	168	$ 1,411,200	$ 1,764,000	1.411	1.764	0.789
Guardian	4	4	168	$ 3,158,400	$ 3,158,400	3.158	3.158	0.690

Table 23. "CAIV Analysis."

Table 23 illustrates the figures described in the CAIV analysis. Flowing from left to right, the cost per flight hour is multiplied by the "# of UASs to Complete Mission" by the duration to get the mission cost (scaled cost = mission cost / 1 million).

3. Future Work

The limited scope of the PMSW&RS project necessitates that some aspects of the system and associated external nodes could only be transiently evaluated. There are additional functionalities, capabilities or solutions that can be further expanded upon.

After looking at multiple UASs one of the key items not discussed by each of the military vendors was integration with existing commercial systems. While this scope was limited to air vehicle functions, perhaps the quickest way to increase capability would involve the integration of command and control with systems such as AIS databases and ship registry databases at the Maritime Security Center, Horn of Africa (MSCHOA). By creating a synthetic AIS registry in an AIS system database, the world would have visibility of suspected pirate mother ships. Suspect pirate mother ships detected and tracked by a UAS could be given synthetic AIS registries which could be broadcast and uploaded into databases used by commercial industry. This would provide wide and instant access to all parties involved. This could represent the most effective way to provide communications quickly to all parties.

Other considerations for future research involve the inclusion of pirate interdiction procedures into the concept of operation. Evolving the systems operational procedure to include interdiction may enhance the anti-piracy activity. One direction may be to consider the use of weaponized UASs with careful consideration given to international legal issues. This system currently stops at the collection, evaluation and transmission of surface contact information, but on-board weapons may dramatically deter piracy. In the absence of the AIS solution presented above, an alternative would be to explore the broadcasting of a warning signal from a UAV to commercial vessels within the HOA AOR directly from the UAV V/UHF radios. Such a signal would provide the location and heading of suspected pirates similar to a weather warning.

Currently, PMSW&RS gathers data on unknown surface contacts and transmits this information to command and control. The role that command and control performs was not evaluated in great detail due to the limited scope of the project. Command and control is responsible for discriminating received information, alerting the commercial vessels of an imminent attack, and organizing piracy interdiction. There is opportunity in future work on processing and dissemination of the gathered ISR data to increase the effectiveness of the anti-piracy activities. The use of AIS could be a method where the identified threat information could be transmitted as a ghost signature for broadcast and display in real time.

APPENDIX A: LIST OF ACRONYMS

Acronym	Term
ADM	Acquisition Decision Memorandum
BAMS	Broad Area Maritime Surveillance
C2	Command and Control
CAIV	Cost as an Independent Variable
CNO	Chief of Naval Operation
DoD	Department of Defense
DON	Department of Navy
GAO	Government Accountability Office
GCS	Ground Control Station
HOA AOR	Horn of Africa Area of Responsibility
INCOSE	International Council on Systems Engineering
IPR	Interim Project Reviews
IPT	Integrated Product Team
ISR	Intelligence, Surveillance, and Reconnaissance
JCIDS	Joint Capabilities Integration Development System
SCIP	Joint UAS Common Control Station
MSSE	Masters of Systems Engineering
NAVAIR	Naval Air Systems Command
NPS	Naval Postgraduate School
OPTEVFOR	Operational Test and Evaluation Force
OT&E	Operational Test and Evaluation
PEO	Program Executive Office
PM	Program Manager
PMP	Project Management Plan
R&M	Reliability and Maintainability
RDT&E	Research, Development, Test and Evaluation
SE	Systems Engineering
STANAG	Standard Agreement
U&W	Unmanned Aviation and Weapons
UAE	United Arab Emirates
UAS	Unmanned Aircraft (or Air) Systems

UAV	Unmanned Aerial Vehicle
UCAS	Unmanned Combat Air Systems
USD (AT&L)	Under Secretary of Defense of Acquisition, Technology, and Logistics
VTUAV	Vertical Take-off and Land Tactical UAV

APPENDIX B: SENSITIVITY ANALYSIS

Figure 42, "Sensitivity Analysis (Detection Range)" shows the weighting factor sensitivity plots for all eight measures of performance. The measures of performance include: Detection range, line of sight, tracking, hours on station, beyond line of sight, detection accuracy range, NIIRS, and speed.

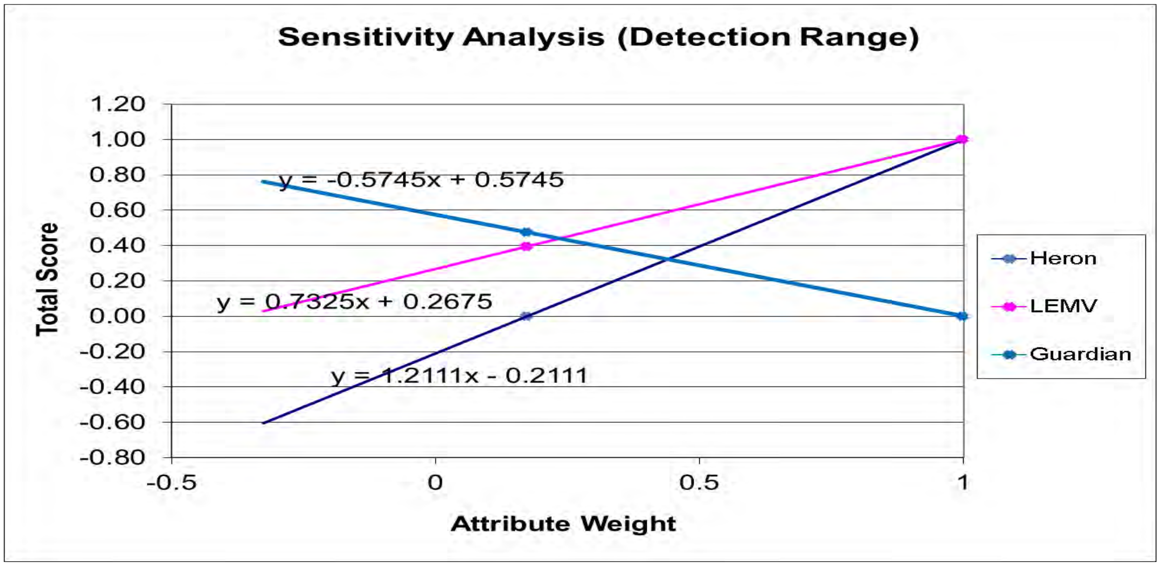

Figure 42. "Sensitivity Analysis (Detection Range)."

Figure 42 shows the weights sensitivity chart for Detection Range Measure of Performance. The alternative with the highest slope is Heron TP with a slope value of 1.2111; therefore Heron TP is the alternative that is most sensitive to weight changes for the Detection Range MOP.

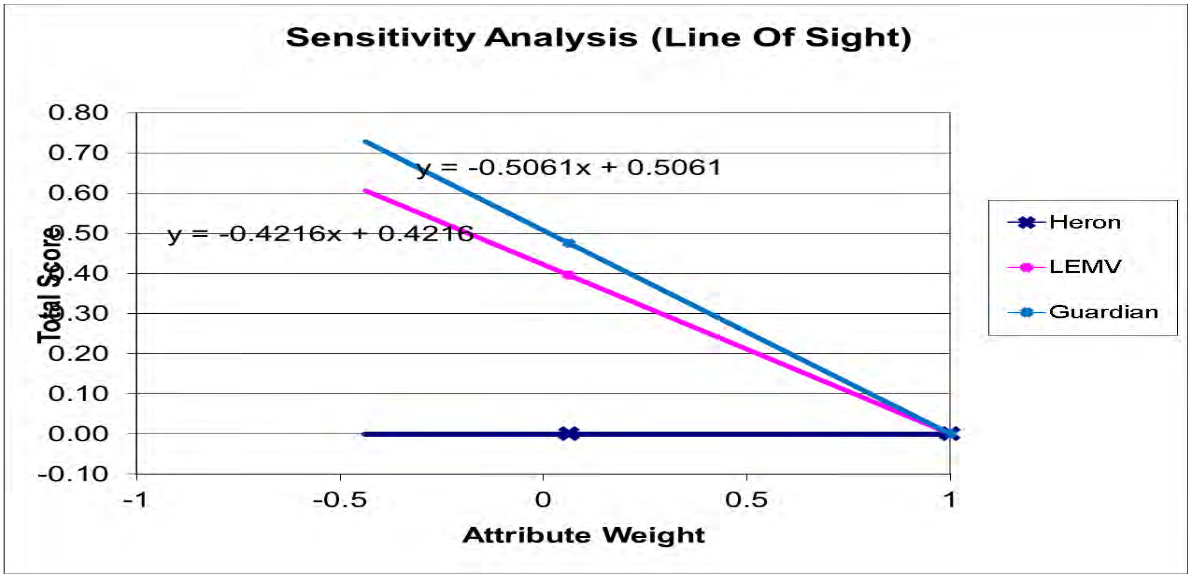

Figure 43. “Sensitivity Analysis (Line of Sight.)”

As shown in Figure 43, the alternative with the highest absolute slope value is Guardian with the absolute slope value of 0.5061; therefore, Guardian is the alternative that is most sensitive to weight changes for the Line of Sight MOP.

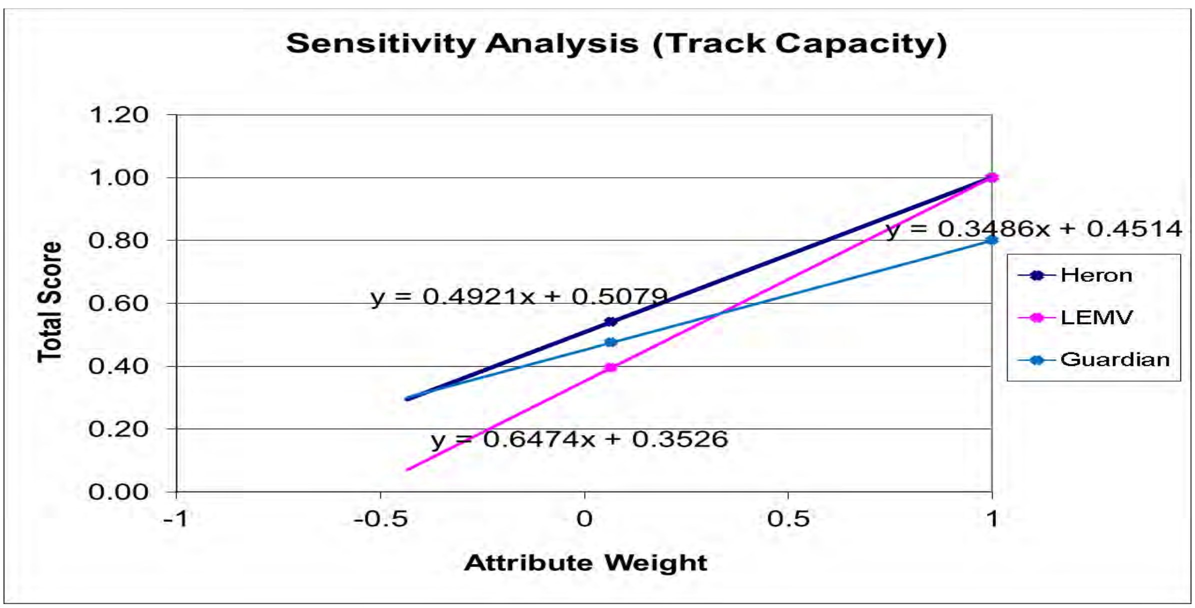

Figure 44. “Sensitivity Analysis (Track Capability).”

Figure 44 shows the weight sensitivity plot for Track Capacity MOP. The alternative with the highest slope value is LEMV with the slope value of 0.6474; therefore, LEMV is the alternative that is most sensitive to weight change for the Track Capacity MOP.

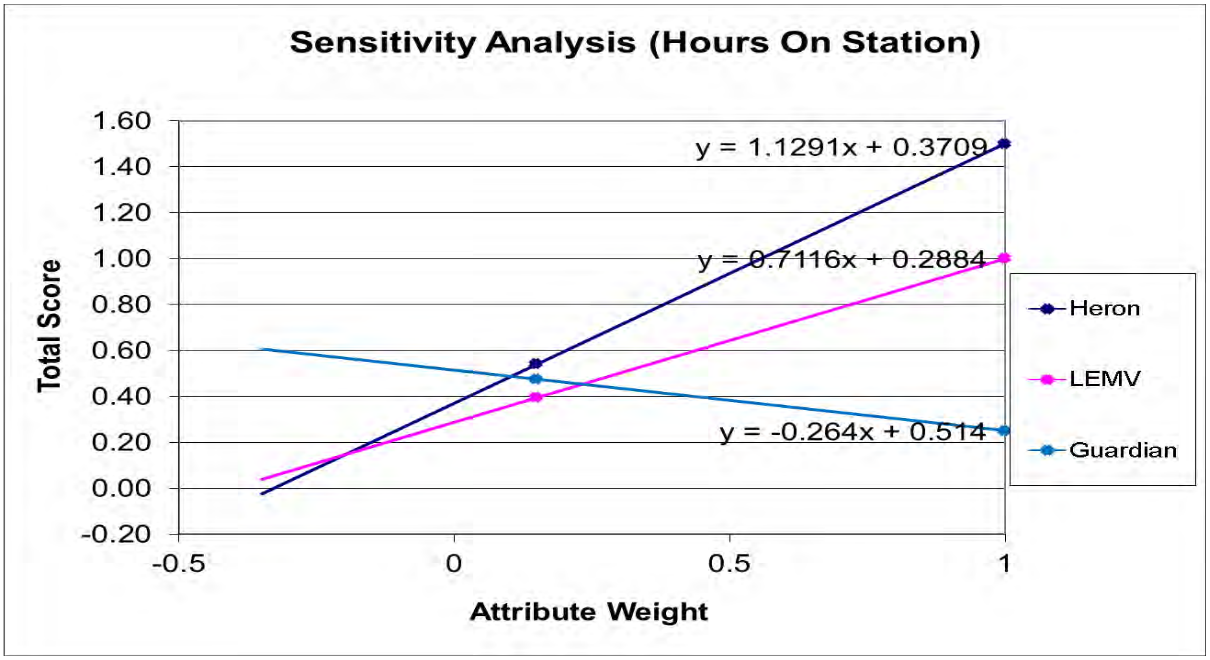

Figure 45. “Sensitivity Analysis (Hours on Station).”

Figure 45 shows the alternative with the highest slope value is Heron TP with the slope value of 1.1291. Heron TP is the alternative that is most sensitive to weight changes for Hours on Station MOP.

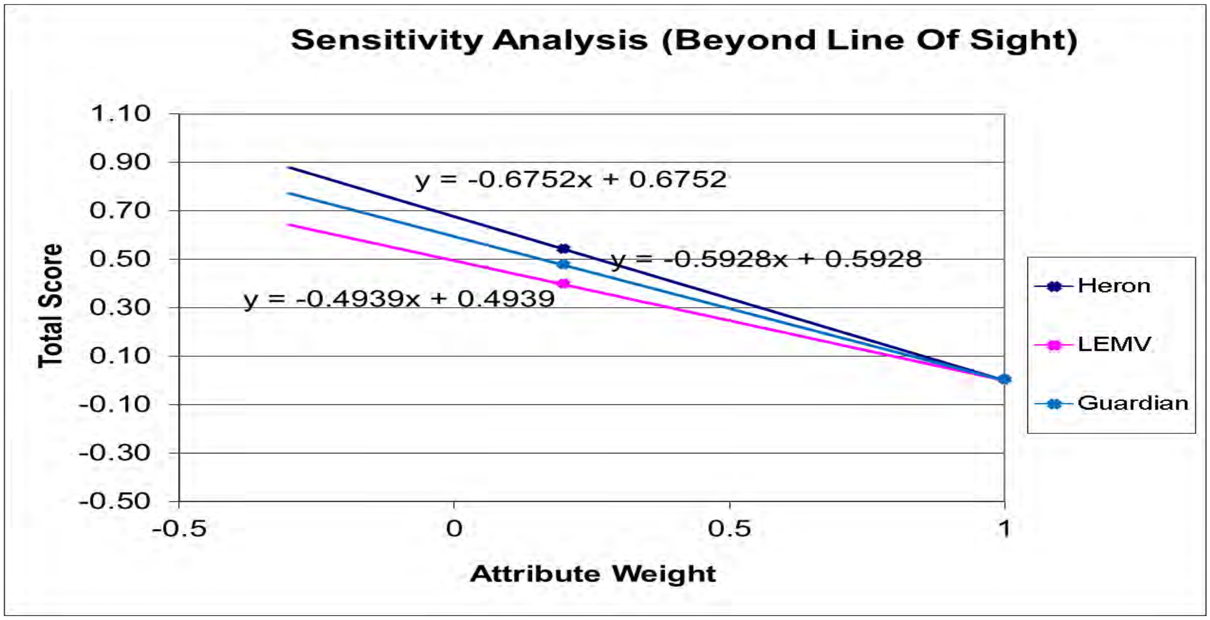

Figure 46. “Sensitivity Analysis (Beyond Line of Sight.)”

Figure 46 shows the alternative that is most sensitive to weight change is Heron TP for Beyond Line of Sight MOP with the absolute slope value of 0.6752.

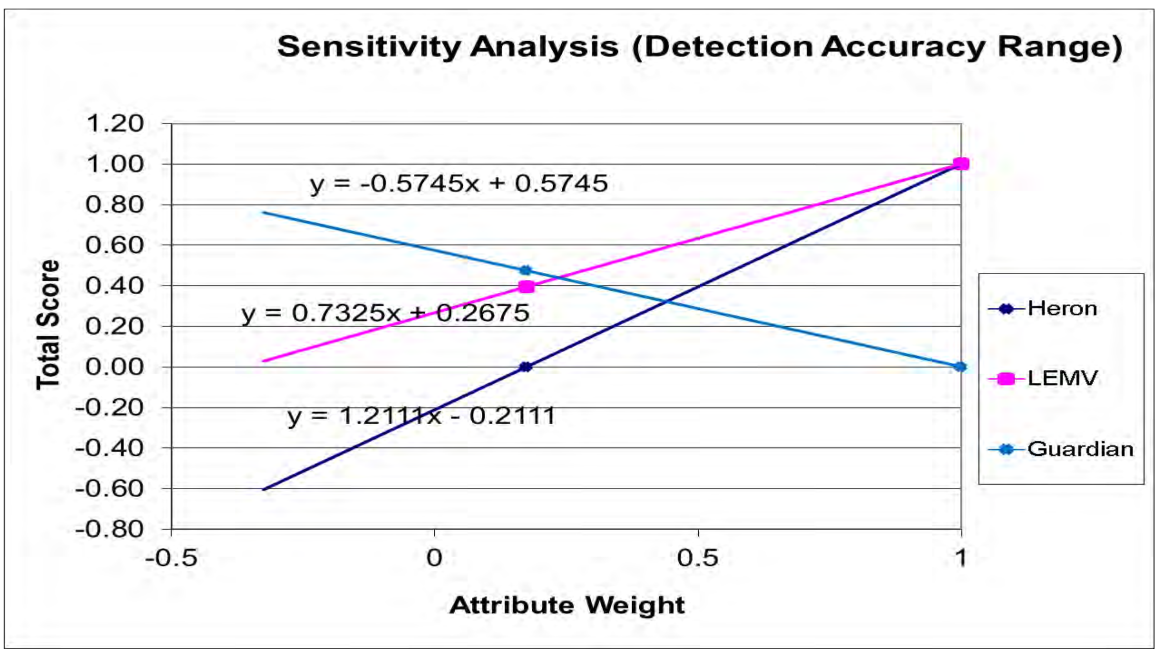

Figure 47. “Sensitivity Analysis (Detection Accuracy Range).”

Figure 47 shows the alternative that is most sensitive to weight change for the Detection Accuracy Range MOP is Heron TP with a slope value of 1.2111.

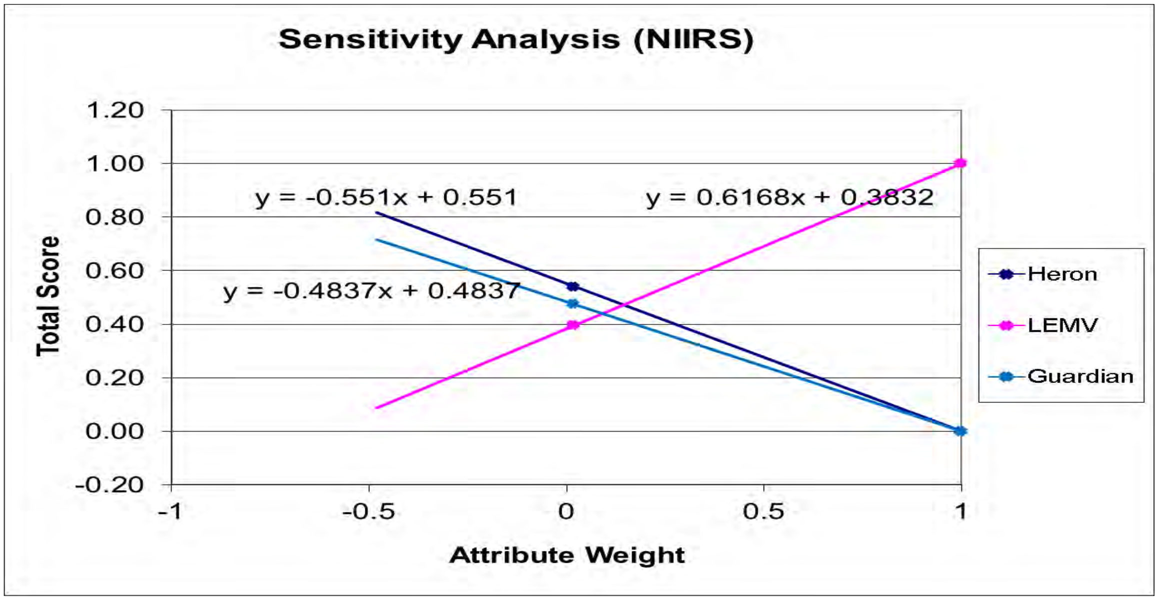

Figure 48. “Sensitivity Analysis NIIRS).”

Figure 48 “Sensitivity Analysis (NIIRS)” shows the alternative that is most sensitive to weight changes is LEMV for NIIRS MOP with a slope value of 0.6168.

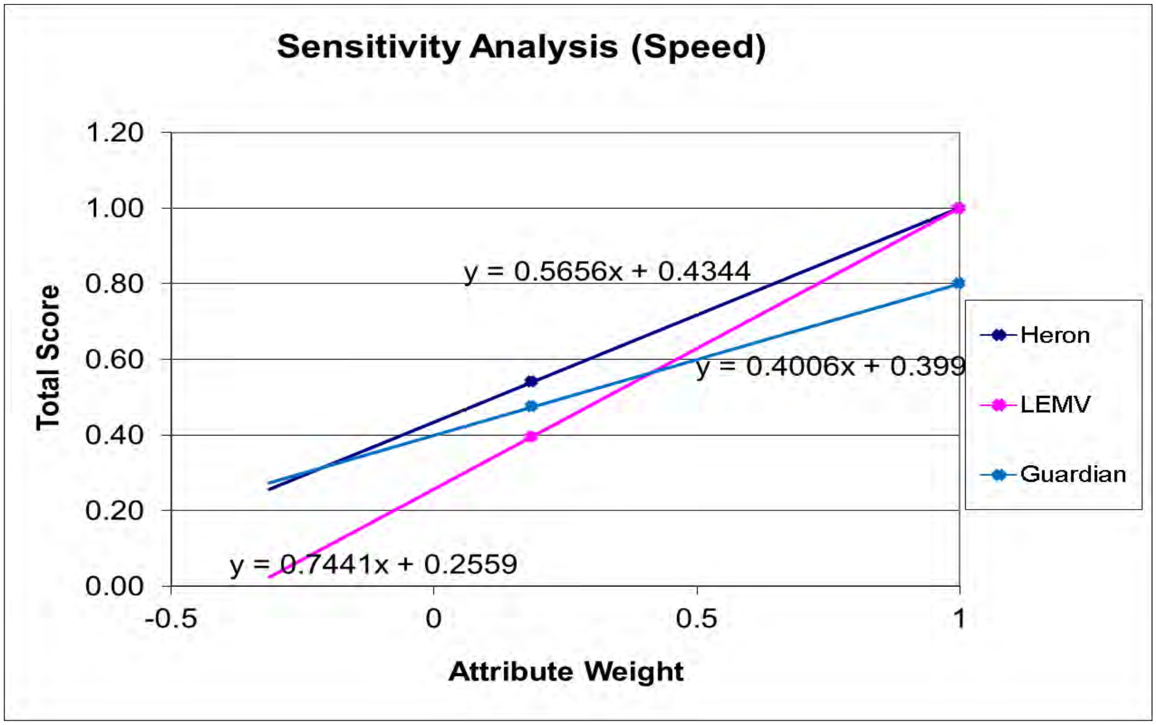

Figure 49. “Sensitivity Analysis (Speed.)”

Figure 49 shows the alternative that is most sensitive to weight change for the Speed MOP is LEMV with the slope value of 0.7441.

APPENDIX C: STAKEHOLDER REFINEMENT

The following stakeholders attended IPR 1 or 2

1. Ron Carlson; rrcarlso@nps.edu
2. Dr. Rama Gehris; rdgehris@nps.edu
3. Dr. Dick Millar; rcmillar@nps.edu
4. Wayne Parsons; wayne.parsons@navy.mil
5. Steve Daniel Stephen.daniel@navy.mil
6. Pete Wolt; peter.wolt@navy.mil
7. Cecil Bradley; cecil.d.bradley@boeing.com
8. Bruce Newell; Burce.newell@boeing.com
9. Dan Gabriel; dan.w.gabriel@boeing.com

The stakeholders' expert opinions and experience provided insight on existing systems, capabilities of specific payloads, data networks, information systems, communication systems, as well as others that were utilized in developing PMSW&RS. Furthermore, the stakeholders' experience alerted the team to other key issues that needed to be considered. The stakeholders that were present during both IPRs come from both the contractor and government sectors which allows for a broad perspective on the end user's wants and needs.

The stakeholders at the first Integrated Project Review (IPR) brought up critical topics that needed to be discussed. One key issue discussed was how to identify potential threats, not only from a friend or foe standpoint, but from a physical standpoint. Descriptions of the capabilities of the sensors on board the Unmanned Aerial System (UAS) are very limited. Basically, how clear would a picture be of a potential threat from twenty thousand feet? Based on the problem descriptions, the stakeholders' contention is the sensors will provide enough detail in the image that an analyst will be able to determine if a pirate has taken over the ship. This leveraged into suggestions that manned assets could complete the mission rather than just restricting potential options of PMSW&RS to unmanned aircraft. A critical constraint mandated is that all assets must be in the field or fielded by FY12. This severely restricts potential solutions available to PMSW&RS.

It was established that a "kill chain" needed to be implemented in PMSW&RS as well as a trigger for the Intelligence, Surveillance, and Reconnaissance (ISR) assets. Stakeholders suggested that a space-based system such as a satellite could be a potential solution. Initial concepts of PMSW&RS call for a 24/7 type of surveillance for an extended duration. The concern is that this type of effort is very expensive. Also, it is questionable how this will affect tracking potential threats if that persistent surveillance is broken. It was determined that projections can be made predicting the path of a ship. This is critical information as an ISR asset could lose track of a ship and be able to regain its position.

Automatic Information System (AIS) was a very important topic that was discussed with the stakeholders. AIS is a line-of-sight based system; a stakeholder that works on another UAS platform indicated that while in the air, this UAS picked up an AIS signal from a ship off the coast of Florida. This information provided some indication of the capability of the AIS system. Further details will need to be researched concerning what information can/needed to be exchanged from a ship to a UAS and if there was an existing data link system already in the field that can be utilized. Essentially, can the AIS data system exchange more than just a location of a ship? A stakeholder then mentioned that there is a problem with "spoofing" an AIS signal. This would mean that there needs to be another method of detection outside of AIS.

Refinement concepts of PMSW&RS continued to be an issue. PMSW&RS is responsible for detection, identification, and tracking of potential pirate threats. All analysis performed will serve as a function of anther system outside of PMSW&RS. With that scope defined, it needs to be determined what data would need to be sent to this analytical system. PMSW&RS must ensure that the right information is sent to the right place.

The second IPR yielded a productive experience in refining and gathering intelligence from the stakeholders. AIS was the first topic discussed. Stakeholders raised concern again about pirates "spoofing" AIS as well as pirates shutting a ships onboard AIS system down. Furthermore, there was discussion on what communications systems were already in existence and how did the pirates communicate with the merchant sailors. A suggestion that was made that to help eliminate this problem was to begin this process before a ship leaves port. All ships must port at some point, and with that comes information as well as a location. There are shipping logs that document the arrival and departure of ships as well and tracking can start there. Tracking and relocating was brought up again, and there was discussion on how to relocate once a ships signal was lost.

Signals analysis and concepts was a critical area of interest. Can we identify a footprint on a radio signal? What are the capabilities of exploiting signals across different frequencies? Can signals analysis aid in the task of classification of a ship as it is the biggest challenge? A few key points were raised through this discussion. One consideration was to mark a ship somehow which will allow an ISR asset to easily come back. Another thought was to regain tracking by identifying a ship's transmitter as no two transmitters are exactly the same.

Calculations for PMSW&RS have to be generated for probability of detection, square miles of the area of interest, and number of assets required to complete the mission. To narrow the area in question the idea was to provide safe passage through specific shipping lanes. This way the entire gulf did not have to be monitored and aggressively cut back the score of the problem. The problem with this idea is that merchant sailors are not using specific lanes because the guarded shipping lanes are indirect to the final destination, and it is costing too much money to travel them.

Data fusion was another challenge for PMSW&RS. With all of the sensors on an ISR asset how can the data be fused together to create usable information? Can an overlay of AIS data onto radar? A stakeholder mentioned a Coast Guard ISR platform called Guardian that has some of the features that were mentioned. It can integrate AIS and overlay it onto radar as well as provide optical files and integrate Electro-optical inferred (EOIR) data. Furthermore, it can merge AIS data with the Global information Grid (GIG). This is a viable option to aid in the solution to this problem.

Direction, scope, and a path forward are all results of the two IPRS. The stakeholders proved to be incredibly knowledgeable and offered keen insight that allowed PMSW&RS to narrow the scope of the problem, provide clarity and knowledge to overcome challenges to make PMSW&RS a solution to the pirating problem.

APPENDIX D: SURFACE RADAR DETECTION REQUIREMENT DEVELOPMENT SUPPORT

The Radar Cross Section (RCS) of an object is a function of the return energy received by a radar system. The RCS value of a target is the return energy density divided by the radar transmitted energy. If an object is small or employs stealth technology, the returned energy will be too small to be successfully processed into a contact by the radar receiver. A small RCS value of a vessel can be masked by the characteristics of the environment it is in. In order to determine the proper surveillance systems best suited the system needs, the team gathered information on the characteristic radar cross section of various types of ships. They needed to determine the minimum sized vessel that the system may have to detect. This will directly affect the probability of detection and is a function of UAS altitude, the power and angle of incident of transmitted energy, and distance from target.

Typical ranges of RCS signatures for various ships can be found in Table 26. The range covers different aspects of transmitted energy or direction of view. The low side of the ranges is indicated with the letters that represent B (Broadside) or S (Stern on) aspects. The high side of the ranges is indicated with one or more letters including those listed above as well as BW (Bow), BWO (Bow On) and Q (Quarterdeck). The smallest vessel listed is an in-shore fishing vessel with a minimum RCS of 3 m^2. The SeaVueTM X-band surveillance radar can detect a 1 m^2 RCS return at 30 miles distance, in a sea state of three at the highest transmitted power setting of 50 kW but at an altitude of only 600 feet (Jane's Intelligence 2011).

Ship RCS Table

(Source: Williams/Cramp/Curtis: Experimental study of the radar cross section of maritime targets. Electronic Circuits and Systems, Vol. 2, No. 4, July 1978, amended by I. Harre, 2004)

Target Ship			Median radar cross section of target vessel, m² (scale: 10, 100, 1,000, 10,000, 100,000, 1,000,000, 10,000,000)		
Type	Overall length (m)	Gross tonnage		approx. min. RCS	approx. max. RCS
Inshore fishing vessel	9	5	Q	3	10
Small coaster	40-46	200-250	S – B/Q	20	800
Coaster	55	500	nS – B/Q	40	2,000
Coaster	55	500	S – BW/Q	300	4,000
Coaster	57	500	Q – BW	1,000	16,000
Large Coaster	67	836-1,000	BW – Q	1,000	5,000
Collier	73	1,570	nB – BW	300	2,000
Warship (frigate)	103	2000*	BW – B	5,000	100,000
Cargo liner	114	5,000	BW – Q	10,000	16,000
Cargo liner	137	8,000	BW/Q – Q	4,000	16,000
Bulk carrier	167	8,200	BW – B/Q	400	10,000
Cargo	153	9,400	BW – BW	1,600	12,500
Cargo	166	10,430	BW – Q	400	16,000
Bulk carrier	198	15,000-20,000	nB – B/Q	1,000	32,000
Ore carrier	206	25,400	BW – nB	2,000	25,000
Container carrier	212	26436**	BW – B/BW/Q	10,000	80,000
Medium tanker	213-229	30,000-35,000	nB – Q	5,000	80,000
Medium tanker	251	44,700	nB – B	16,000	1,600,000

* Displacement
** Considerable deck cargo
S = stern on
Q = quarter
B = broadside
BW = bow
BWO = bow on
n = near

Table 25. “List of Ship Cross-Section.

APPENDIX E: ADDITIONAL ARCHITECTURE CHARTS AND GRAPHS

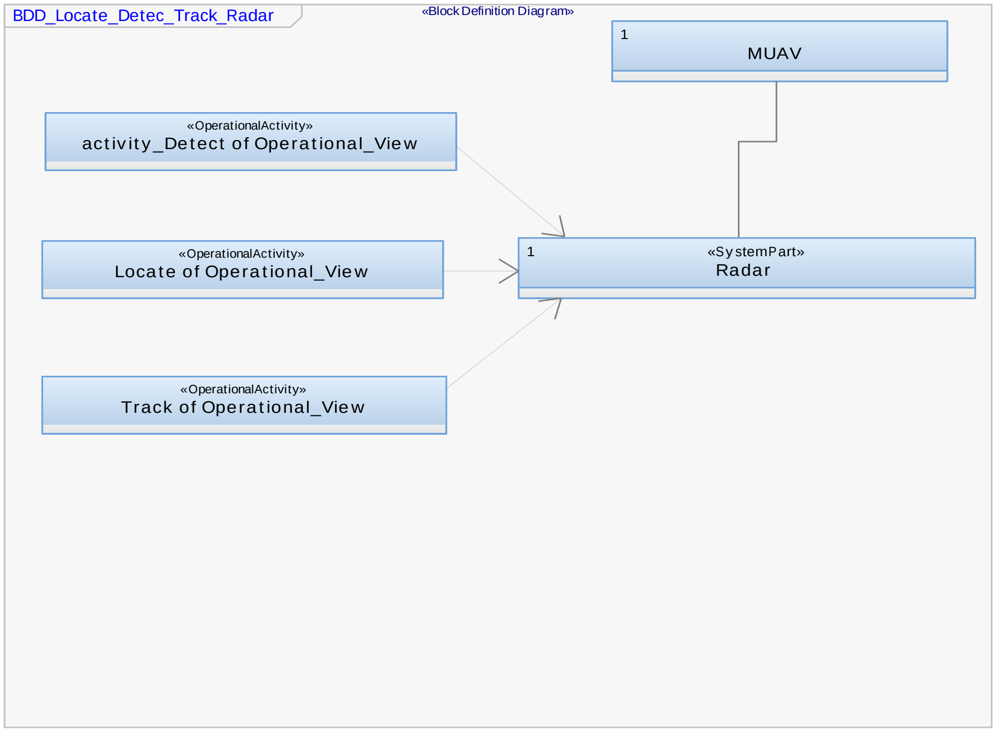

Figure 50. “Operational Activities to Systems”

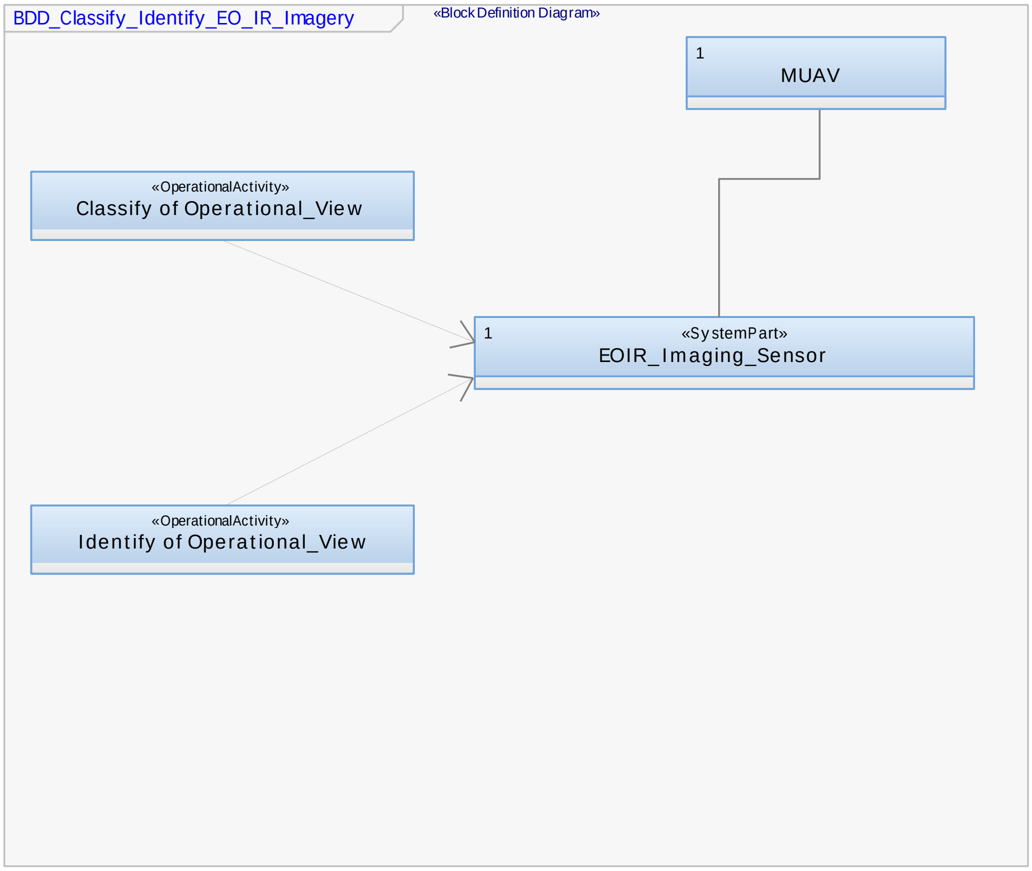

Figure 51. “Operational Activities to Systems.”

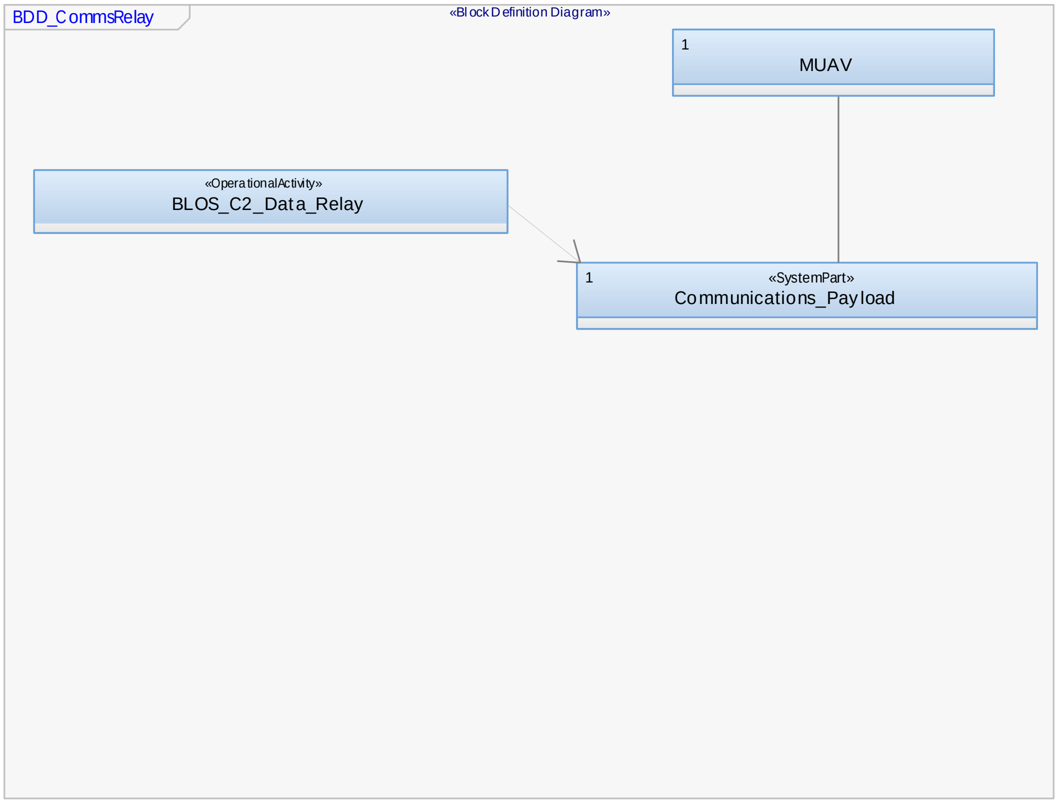

Figure 52. “Operational Activities to Systems.”

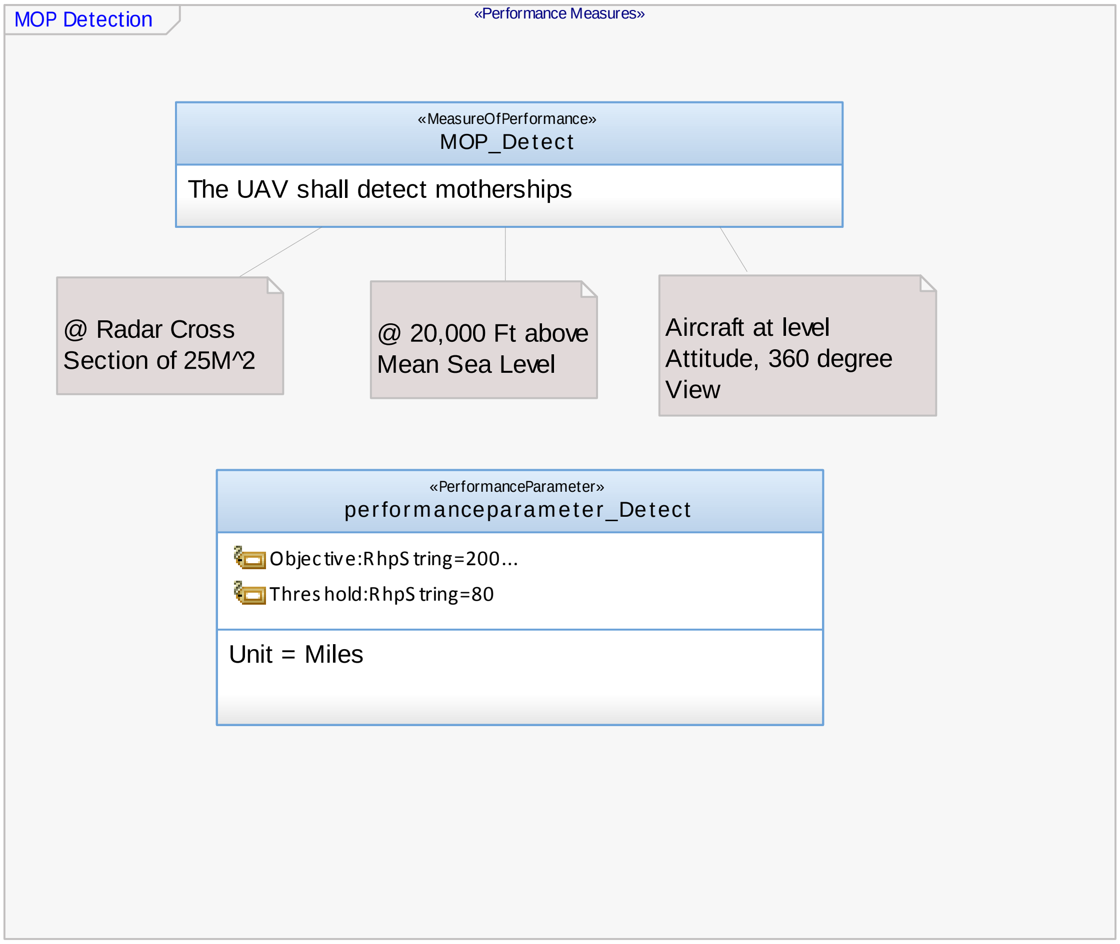

Figure 53. “MOP Detect.”

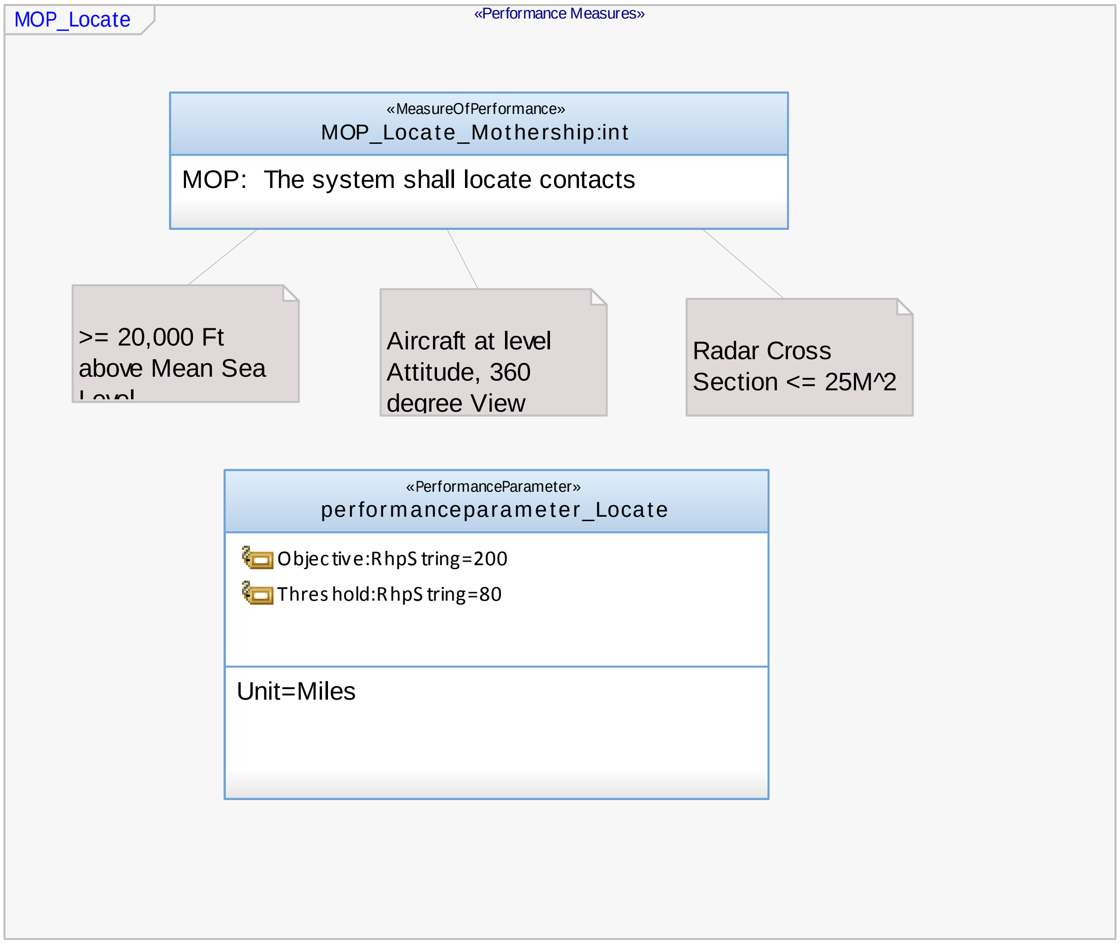

Figure 54. "Locate Mothership."

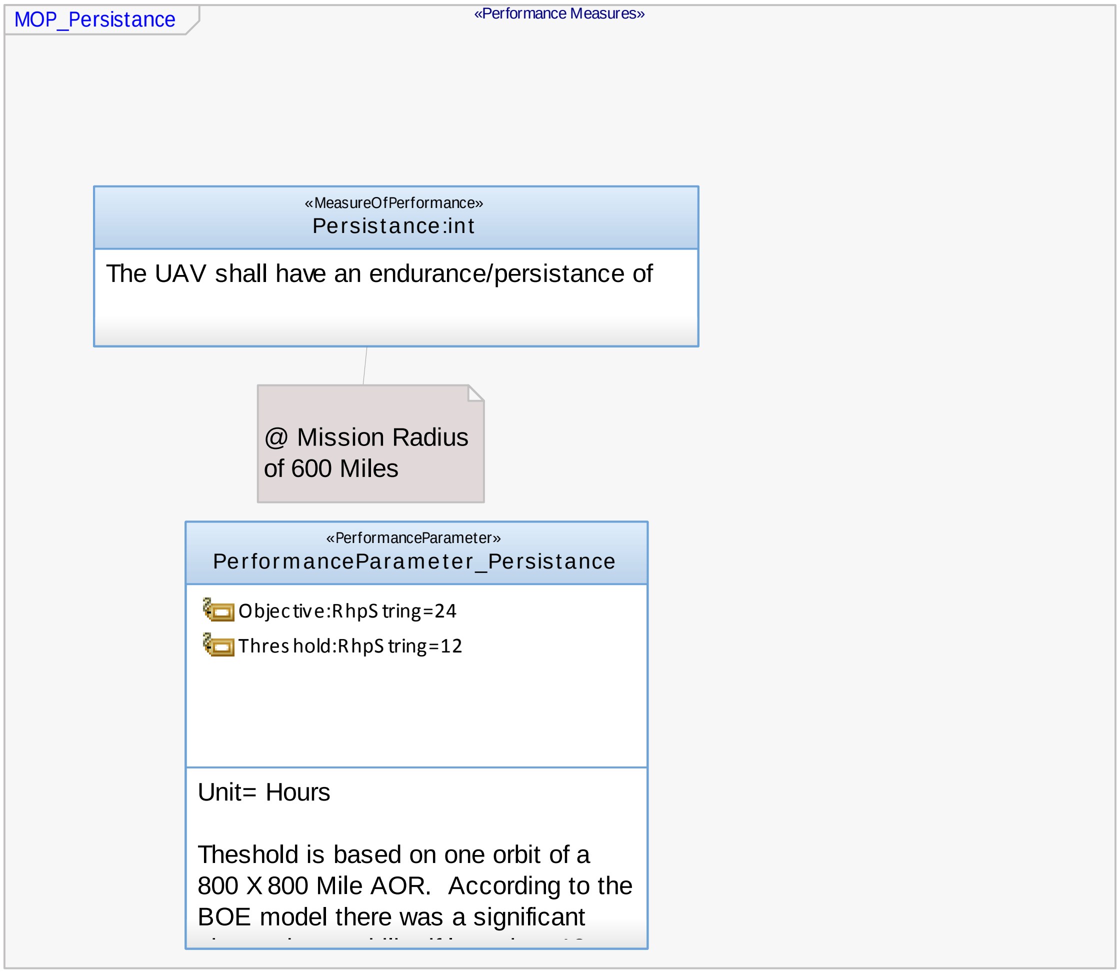

Figure 55. "MOP Persistence."

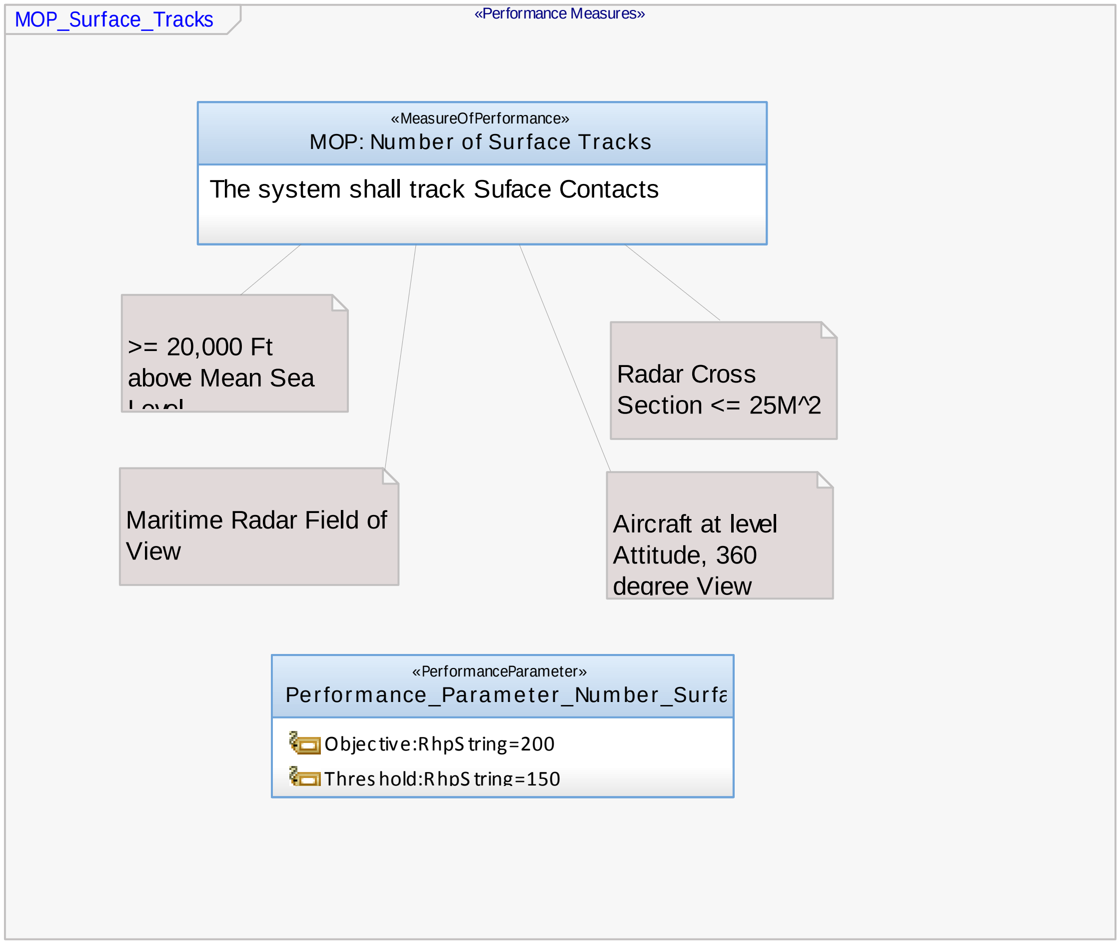

Figure 56. "MOP Surface Tracks."

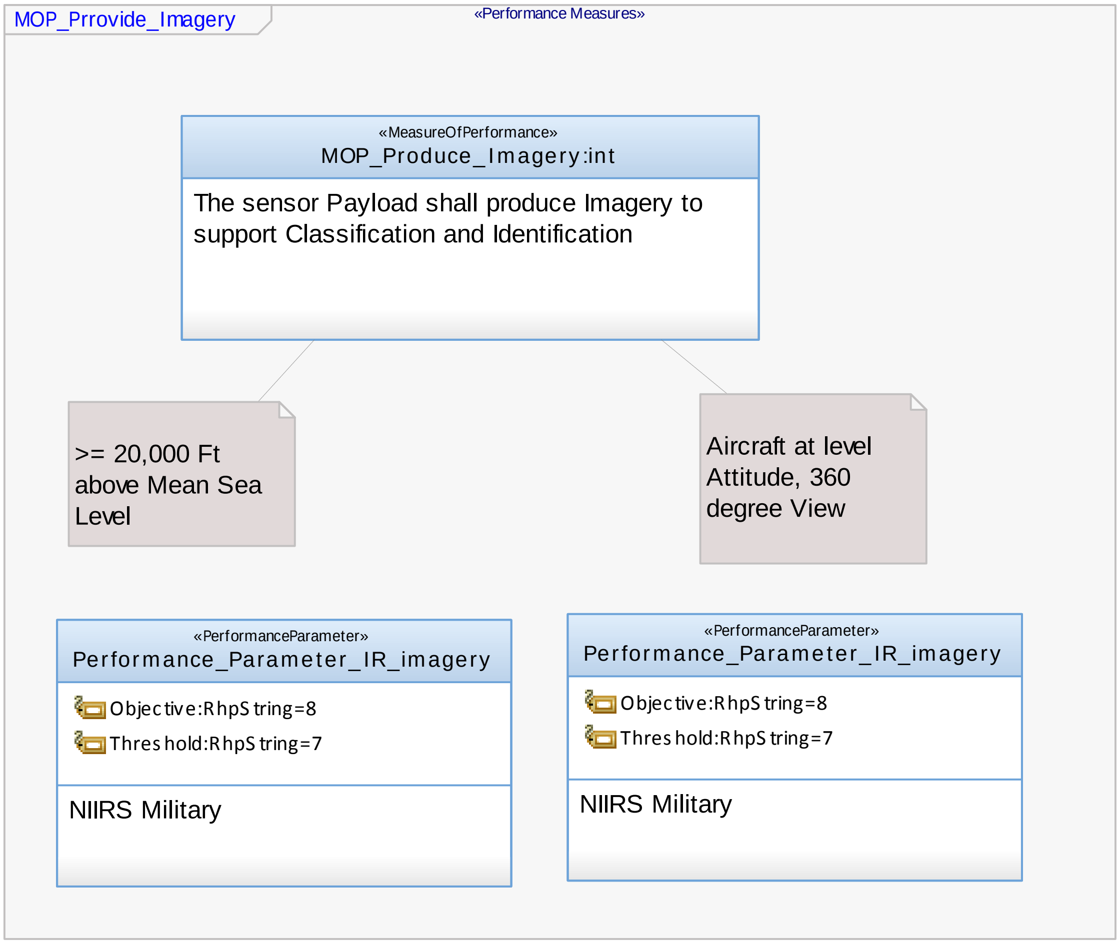

Figure 57. “MOP Imagery.”

Not Squawking AIS
Stationary, little to no movement (In Commercial lane=Greater probability)
Small vessels operating alongside
Towing of small vessels/skiffs
High speed maneuvering with rapid changes in velocity
Spoofing AIS
Erratic course changes
SigInt (typically classified)

Table 26. "Discriminators for Broad Area Detection."

APPENDIX F: MODELLING USING EXCEL SOFTWARE

Modeling and simulation allows for the examination of system performance before it is built as well as performing an analysis of alternative solutions in determining the best set of components to use in the system. For the purpose of this project, two EXCEL models were used to evaluate the tradeoff of system requirements such as number of UASs, speed of UAVs, UAV endurance time, UAS radar range, the required warning we want to give commercial vessels, and the size of the patrol area. Using these inputs the models will compute the theoretical system results of the probability of success for detecting enemy mother ships with enough time to warn commercial vessels of an imminent attack. The early model was used to simulate the first concept of using a medium altitude UAS launched from a land-based site to perform pirate ship detections and tracking, and a low altitude UAS launched from a sea based asset for EO identification. After considering the high expense and issues of requiring a sea-based asset for launching UASs, a second concept model was developed to simulate a pure medium altitude UAS launched from a land-based site. These UASs will operate at a medium altitude level and will be able to dip to a lower altitude also to perform identification. These models allow for the adjustment of each parameter to determine the impact to the system's successful detection capability for various possible configurations.

The team needed to ascertain the size of the patrol area that could successfully be patrolled. Too big of an area could result in ineffective support and early warning alerts for the commercial vessels from pirate attacks. In the same manner, a patrol area that is too small, results in an unnecessary constrictive burden to the commercial shipping by forcing a narrow corridor of safety. Because of the large number of variables between the possible components of the system, the modeling would determine the proper scanning area size for each system configuration.

Another factor was the uncertainty in the number of UASs needed to cover the area of interest that would give a satisfactory probability of success. The inherent differences of performance (speed of UAV, Speed of target vessels, operational altitude, and time on site, etc.) between each potential ISR platform made it necessary to create a model. All parameters discovered during the product research effort were used as inputs into the model to generate the needed results. Using the model results would allow definition of quantitative factors for use in the final system configuration that best meets customer needs. These and other factors were evaluated using the models.

The model was used to help determine thresholds and objectives for system level MOPs such as UAV speed, UAV endurance, and radar range. Starting with the median values of currently available UAS capabilities as inputs to the model, each MOP was adjusted individually to determine the necessary value that achieves the system's detection threshold and objective. The initial median values that were used for speed, endurance, and radar range are 150 knots, twenty hours, and sixty nautical miles respectively and the results are shown in Table 27.

	UAV Speed	UAV Endurance	Radar Range
Threshold	100 knots	12 hours	80 nm
Objective	200 knots	24 hours	200 nm

Table 27. "UAV MOPs Threshold and Objective."

Two Concepts Modeled

There are two operational concepts that were modeled using a "Back of Envelope" (BOE) simulation using Microsoft EXCEL. The first concept used Medium Altitude UASs launched from a land-based site to perform the scanning and tracking of all ships within the preselected zone. When an unidentified ship meets predetermined criteria for a pirate mother ship, this potential target will trigger a low altitude UAS launch from a ship-based site located within the patrolled area to perform detailed classification and identification of friend or foe. The number of medium altitude UASs, low altitude UASs, protection zone size, distances from ship and land base launch sites, UAV speed, UAV endurance, refueling times and the required warning distance for commercial vessels have been evaluated. The results of this model compared and traded off these factors and the various UASs available to use with the system to yield the best probabilistic percentage of successful detections. The values shown in Table 29 are the results for the different UASs used in when considering the separate medium +_low configuration.

	UAV	Model Type	# of UAV's needed to meet threshold (80%)	# of UAV's needed to meet goal (90%)
High and Low alt UAVs	Heron & Scan Eagle	Medium Alt UAV & Low Alt Ship launched UAV	MA UAV's: 2 LA UAV's: 2 (96%)	MA UAV's: 2 LA UAV's: 2 (96%)
	LEMV & Scan Eagle	Medium Alt UAV & Low Alt Ship launched UAV	MA UAV's: 3 LA UAV's: 2 (88%)	MA UAV's: 4 LA UAV's: 2 (98%)
	Guardian & Scan Eagle	Medium Alt UAV & Low Alt Ship launched UAV	MA UAV's: 3 LA UAV's: 2 (96%)	MA UAV's: 3 LA UAV's: 2 (96%)
	Heron & Fire scout	Medium Alt UAV & Low Alt Ship launched UAV	MA UAV's: 2 LA UAV's: 2 (98%)	MA UAV's: 2 LA UAV's: 2 (98%)
	LEMV & Fire scout	Medium Alt UAV & Low Alt Ship launched UAV	MA UAV's: 3 LA UAV's: 2 (97%)	MA UAV's: 3 LA UAV's: 2 (97%)
	Guardian & Fire scout	Medium Alt UAV & Low Alt Ship launched UAV	MA UAV's: 3 LA UAV's: 2 (98%)	MA UAV's: 3 LA UAV's: 2 (98%)

Table 28. "Concept 1 Model Output." UAS type and quantity tradeoff.

It was found that to meet the threshold of 80% successful detection, the system needed to have a protection zone size no larger than 800 by 800 nm and a minimum of two medium altitude UASs with two low altitude UASs. However, the team learned that payloads were available for medium altitude UASs able to perform EO/IR identification and classification at their cruising altitudes. The medium and low altitude UAS concept was set aside to consider the simpler and potentially more cost effective solution of using medium altitude UASs for all ISR functions.

The second concept uses only UASs that fly at medium height altitude launched from a land-based site. These medium altitude UASs will be able to fly to the protection zone, scan the area for potential mother ships, and when the predetermined criteria is met, as defined in the medium +_low concept. For a potential mother ship the medium altitude UAS will decrease altitude, if necessary (depending on UAS and radar package capability), and perform EO/IR identification. This option will not require a ship-based launching capability and does not need low altitude UASs to perform EO/IR identification. When the UAS is done identifying the ship, it will return to a scanning function. The number of medium altitude UASs needed, protection zone size, distances from land base launch sites, UAV speed, UAV endurance, UAS payload detection range, refueling times, the required warning distance for commercial vessels, and the percent of successful detections have been evaluated. The results of this model also compared and traded off these factors and the various UASs available to use with the system to yield the best probabilistic percentage of successful detections. The values shown in Table 30 are the results for the different UASs used in medium altitude only configuration.

	UAV	Model Type	# of UAV's needed to meet threshold (80%)	# of UAV's needed to meet goal (90%)
MA UAVs	Heron	Med Alt UAV's only	MA UAV's: 3 (85%)	MA UAV's: 4 (98%)
	LEMV	Med Alt UAV's only	MA UAV's: 6 (80%)	MA UAV's: 7 (94%)
	Guardian	Med Alt UAV's only	MA UAV's: 5 (92%)	MA UAV's: 5 (92%)

Table 29. "Concept 2 Model Output." UAS Type and quantity tradeoff.

To meet the threshold of 80% successful detection, the system could achieve this with only three medium altitude UASs. This concept was then considered superior because it requires less operational UASs than medium + low concept, and it can be completely operated and maintained from a land-based launch site requiring less specialized equipment, manpower, and Navy assets.

Probabilistic nature of the model

To accurately model pirate ship attacks upon commercial freighters, the model has two statistical input variables for entering known historical data of pirate ship attacks: mean time between attacks and the associated variance. Using the historical data from the ICC-IMB 2010 annual piracy report, the calculated mean time between attacks is forty-five hours with a variance of 20.3 hours (ICC-International Maritime Bureau 2010). These values are used to generate the random times each mother ship will enter the protection zone. Another normally distributed random variable is used to determine where the pirate ship enters the protection zone in relation to the UASs scanning the area. By randomly varying this distance between the pirate vessel entering the protection zone and the UAS, it will take the UAS varying amounts of time to perform initial detection of that pirate vessel. This initial detection time along with the pirate vessel speed will determine the distance of penetration into the protection zone. Using these probabilistic values and specific UAS characteristics, the model will determine the probability of system success.

Model Mechanics

The model first models the back and forth scanning pattern and path length that the UASs will use to scan the entire protection zone. By using the inputted dimensions of the protection zone and the UAS payload radar range, the number of zigzags needed for the radar to cover the entire protection zone will be calculated and then the overall path length can be calculated. The inputted number of UASs will determine the time and distance spacing between the UASs along the path when they are performing round-the-clock take offs, flying to the protection zone, scanning, returning, and refueling. While the UASs are scanning, a pirate ship is randomly generated and enters into the protection zone at a random location and at a constant speed. Depending on the UAV speed and distance to the generated pirate ship, the model will calculate how far into the protection zone the pirate ship has penetrated before first detection by the next UAS. The next step is to calculate the time needed to perform the final identification and classification, which differs for the two concepts. For medium + low concept, the model will calculate and sum up the time it will take for a low altitude UAS to be launched from a Navy asset located within the protection zone, the time needed to fly to the pirate ship, and the time required to perform EO/IR identification of Friend-or-Foe. For the medium only concept, the model will calculate and sum the UAS descent time, if needed, for the selected medium altitude UAS to fly down to a lower altitude to perform EO/IR identification and the time needed to perform the EO/IR identification and classification. These calculated times along with the pirate ship speed are used to determine the final pirate ship distance into the protection zone. If that particular pirate ship is detected before it reaches the minimum warning distance, then that simulation is counted as a successful detection. The overall system successful detection rate is calculated by simulating one thousand randomly generated pirate attacks and calculating the percentage of system success out of the one thousand attacks.

Simulation Input Paramter	Type	Units	Default Value
Protection Zone width	Variable	nm	1000
Protection Zone length	Variable	nm	1000
mothership velocity	Variable	kt	18
Number of med Alt. UAVs	Variable	Number	2
med Alt UAV flying Altitude	Variable	feet	20000
med Alt UAV scan range (radius)	Derived	nm	20
med Alt UAV speed	Variable	kt	300
med Alt UAV Edurance time	Variable	hr	27
med Alt UAV Ship/Base to zone travel time	Variable	hr	4
med Alt UAV Refueling time	Variable	hr	2
Low Alt UAV speed	Variable	kt	80
Low Alt UAV Set-up and Launch time	Variable	hr	1
Low Alt UAV Ship to protection zone (if not in zone)	Variable	nm	200
Low Alt UAV Ship to zone time (if not in zone)	derived	hr	3
Low Alt UAV round trip time/#UAVs	derived	hr	1
Number of Low Altitude UAV's on hand	Variable	Number	1
Motherships time between attacks	Variable	(mean) hr	20
Width of UAV Scan Area	derived	nm	800
Length of UAV ScanArea	derived	nm	800
Number of Zig Zags needed to scan entire zone	derived	Number	6
Length of Zig Zag pattern	derived	nm	650.0
Width of Zig Zag pattern	derived	nm	650.0
Distance between Zig Zags needed to scan entire zone	derived	nm	133.3
Total number of Zig Zags	derived	Number	6
Total Distance of Zig Zag scan path	derived	nm	5200.0
Number of hi alt UAVs scanning at a time (considering overlap)	derived	Number	2.1
Search Distance between UAV	derived	nm	2453
Max distance across Scan zone from center of scan zone	derived	nm	565.69
Required pirate time Warning around commerical ship	variable	hr	6
Required protection Distance around ship	constant	nm	102
med Altitiude UAV radar detection accuracy	constant	Percent	90
Low Altitude EO/IR detection accuracy	constant	Percent	90

Table 30. “Simulation Input Parameters.”

This is a list of input parameters use in the Microsoft Excel model to determine overall system performance under various configurations.

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